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Mussel Farming as an Example

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INTEGRATING THE ECOSYSTEM SERVICE CONCEPT INTO BALTIC SEA MARINE SPATIAL PLANNING

MUSSEL FARMING AS AN EXAMPLE

BY
MIRIAM VON THENEN

DISSERTATION SUBMITTED 2020

AALBORG UNIVERSITY
DENMARK

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CV

Miriam von Thenen received her B.ASc. in coastal and marine management from the van Hall Larenstein University of Applied Science in Leeuwarden, the Netherlands, in 2014. In 2016, she received her M.Sc. in marine science from the University of Southern Denmark. In her M.Sc. thesis, she used an agent-based model to analyze the spatial distribution of eelgrass seeds in shallow estuaries in Denmark. After a brief excursion into Arctic research at the Geological Survey of Denmark and Greenland at the beginning of 2017, she was employed as a marine scientist at the Leibniz Institute for Baltic Sea Research in Warnemünde, Germany. There she started working in the BONUS BASMATI project (Baltic Sea Maritime Spatial Planning for Sustainable Ecosystem Services) and was accepted as a PhD fellow at Aalborg University in September 2017.

ENGLISH SUMMARY

The seas and oceans are increasingly under pressure from existing and emerging marine uses. There can be conflicts between marine users and the marine environment as well as between and among the different users. A tool to avoid these conflicts and to create synergies is marine spatial planning (MSP). MSP is a planning process with the aim to allocate marine uses spatially and temporally in order to achieve social, economic, and ecological objectives. There is a need for sustainable planning and management of the oceans because they are essential for human well-being, e.g. through the provision of living resources such as fish, the capacity of certain habitats to provide flood control, and to provide a place for recreation and inspiration. These contributions of marine ecosystem to human well-being are called ecosystem services (ES). The ES concept is part of the ecosystem-based approach to MSP that recognizes the importance of the goods and services provided by the sea to society. While there a parallels between the ES concept and MSP, there are a number of challenges when it comes to the integration of ES in MSP. These challenges include the clarification of the ES concept for its use in MSP on a conceptual level; the measurability of ES; and how the ES concept can contribute to MSP site selection. The objective of this thesis is to provide pathways to resolve these challenges and to demonstrate how the ES concept can support and advance MSP.

Three research questions address the challenges and a working framework guides the integration of ES in MSP. The working framework couples the Drivers-Pressures-State-Impacts-Response framework, used by the European Environment Agency, with the ecosystem cascade. The ecosystem cascade pictures ES as the link between ecosystems (environmental system) and the benefits provided to society (socio-economic system). The clarification of the ES concept is approached on a conceptual level, whereas the generation of data in relation to ES and site selection is focusing on one marine use in the Baltic Sea – mussel farming.

In order to facilitate the use of ES in MSP processes, the thesis identifies the need to clarify the ES concept and its link to MSP, to include abiotic ES, and to operationalize ES with indicators, i.e. proxies to quantify ES. For the first research question, data is collected through a scoping and literature review and indicators are analyzed with respect to the ecosystem cascade. The thesis shows that ES assessments following the ecosystem cascade have fundamental links to MSP data requirements in the stocktaking and scenario analysis phases of MSP. In order to use the cascade instrumentally, an ES indicator pool is developed to support ES assessments in MSP. A list of biotic and abiotic ES is provided along with examples that show in which ways the oceans can contribute to human well-being. On a conceptual level, the thesis contributes to the development of a sustainability assessment framework for MSP (MSP-SA), which includes the claim on sea space as the connecting link between marine uses and the ecosystem capacity to produce ES. In the MSP-SA, three impact

categories are identified. These categories are based on the cascade and cover the ecosystem capacity, the ES, and (distribution of) benefits. The latter can support social sustainability aspects in MSP, which is a major contribution of the ES concept to MSP processes by providing an entry point for stakeholder involvement. Underlying the MSP-SA is, furthermore, the idea that there are different interaction types in the marine space between the users, the environment, and the beneficiaries of ES.

In the second part of the thesis, required data to estimate ES are explored using mussel farming as an example. Data on environmental parameters are both combined and transformed for this estimation. The combination of the data is accomplished with a GIS suitability analysis and includes considerations of user-user and user-environment conflicts and synergies. This combination of data provides an overview of the ecosystem capacity to sustain mussel farming in the south-western Baltic Sea. The transformation of environmental data to provide estimates of ES is accomplished with a farm scale model – a dynamic energy budget model (DEB) integrated into a 3D model, using the FlexSem modelling framework. Both the ecosystem capacity and ES are part of the environmental system, whereas the benefits are realized in the socio-economic system.

The thesis approaches the collection of data relating to benefits through two surveys. Based on the surveys, a marine planning framework for site selection based on ES is developed. This framework departs in the MSP-SA applied to mussel farming. Through the last contribution, the thesis shows that the ES concept can be used to structure the planning process, by helping to define a normative vision and strategic objectives, and by applying an ES assessment within the operational phase. Furthermore, the planning framework exemplifies how the different user-environment-beneficiary interactions can be used to bring conflicting perspectives and interests on the table.

The findings from this PhD contribute to a conceptual understanding of the links between ES and MSP and provide entry points for stakeholder involvement. The thesis suggests that the integration of ES in MSP can be mutually reinforcing for the benefit of both – through the focus on the goods and services that should be provided from a planning area and the emphasis on benefits and beneficiaries of ES in the planning process. The PhD, furthermore, illustrates how the ES concept can embed site selection into the MSP process. On an instrumental level, the thesis provides tools to facilitate ES assessments through the indicator pool, a toolbox for the GIS suitability analysis, and the farm scale model. The thesis provides a starting point for applying the ES concept in MSP practices and recommends that future research should investigate the role of the ES concept for the evaluation of existing marine plans and for developing a coherent network of areas that are important for marine conservation and human well-being.

DANSK RESUME

Havene og oceanerne er i stigende grad under pres fra eksisterende og nye marine anvendelser. Der kan være konflikter mellem marine brugere og havmiljøet samt imellem og blandt de forskellige brugere. Marin fysisk planlægning (MSP) er et værktøj til at undgå disse konflikter og til at skabe synergier. MSP er en planlægningsproces med henblik på at allokere marine anvendelser i tid og rum for at opfylde sociale, økonomiske og økologiske målsætninger. Der er behov for bæredygtig planlægning og forvaltning af oceanerne, fordi de er essentielle for menneskers livskvalitet, f.eks. gennem ydelse af levende ressourcer såsom fisk, bestemte levestederes kapacitet til bekæmpelse af oversvømmelser, og at være et sted til rekreation og inspiration. Marine økosystemernes bidrag til menneskers livskvalitet kaldes økosystemtjenester (ES). ES konceptet er en del af den økosystembaserede tilgang til MSP, der anerkender betydningen af de varer og tjenester, som havet leverer til samfundet. Selvom der er paralleller mellem ES konceptet og MSP, er der en række udfordringer med hensyn til integrationen af ES i MSP. Disse udfordringer omfatter præciseringen af ES konceptet til brug for MSP på et konceptuelt niveau; målbarheden af ES; og hvordan ES konceptet kan bidrage til valg af MSP steder. Afhandlingens formål er at præsentere veje til at løse disse udfordringer og at demonstrere, hvordan ES konceptet kan understøtte og fremme udviklingen af MSP.

Tre forskningsspørgsmål adresserer udfordringerne og en arbejdsramme guider integrationen af ES i MSP. Arbejdsrammen kobler rammerne Drivers-Pressure-State-Impacts-Response, der bruges af Det Europæiske Miljøagentur, med økosystemets kaskade. Økosystemets kaskade viser ES som forbindelsen mellem økosystemer (miljøsystem) og de goder, der leveres til samfundet (socioøkonomisk system). Præciseringen af ES konceptet beskrives på et konceptuelt niveau, hvorimod generering af data i forhold til ES og valg af sted fokuserer på en enkelt marin anvendelse i Østersøen – muslingeopdræt.

For at lette brugen af ES i MSP processer identificerer afhandlingen behovet for at afklare ES konceptet og dets forbindelse til MSP, at inkludere abiotiske ES og at operationelisere ES med indikatorer, dvs. proxyer til at kvantificere ES. For det første forskningsspørgsmål indsamles data gennem en scoping og litteraturgennemgang, og indikatorer analyseres med hensyn til økosystemets kaskade. Afhandlingen viser, at ES vurderinger efter økosystemets kaskade har grundlæggende forbindelser til MSP datakrav i statusopgørelsen og scenarieanalysefasen af MSP. For at bruge kaskaden instrumentalt udvikles en ES indikatorpulje til at understøtte ES vurderinger i MSP. En liste med biotisk og abiotisk ES findes sammen med eksempler, der viser, på hvilke måder oceanerne kan bidrage til menneskers livskvalitet. På et konceptuelt niveau bidrager afhandlingen til udviklingen af en bæredygtighedsvurderingsramme for MSP (MSP-SA), som inkluderer krav om havplads som forbindelse mellem marine anvendelser og økosystemets kapacitet til at producere ES. I MSP-SA identificeres tre

påvirkningskategorier. Disse kategorier følger kaskaden og inkluderer økosystemkapacitet, ES og (distribution af) fordele. Sidstnævnte kan understøtte sociale bæredygtighedsaspekter i MSP, som er et vigtigt bidrag fra ES konceptet til MSP processer ved at tilvejebringe et indgangspunkt for involvering af interessenter. Underliggende MSP-SA rammen er endvidere den idé, at der er forskellige interaktionstyper i havområder mellem brugerne, miljøet og ES modtagere.

I anden del af afhandlingen undersøges de nødvendige data for at estimere ES ved hjælp af muslingeopdræt som et eksempel. Data om miljøparametre både kombineres og transformeres med henblik på denne beregning. Kombinationen af dataene udføres med en GIS-egnethedsanalyse og inkluderer overvejelser om bruger-bruger og bruger-miljø konflikter og synergier. Denne kombination af data giver et overblik over økosystemets kapacitet til at opretholde muslingeopdræt i det sydvestlige Østersøen. Transformationen af miljødata for at give estimater af ES gennemføres med en "farm scale" model – en dynamisk energibudgetmodel (DEB) integreret i en 3D-model ved hjælp af FlexSem modelleringsrammen. Både økosystemets kapacitet og ES er en del af miljøsystemet, mens fordelene realiseres i det socioøkonomiske system.

Afhandlingen tilgår indsamling af data vedrørende fordele gennem to undersøgelser. Baseret på undersøgelserne udvikles en havplanlægningsramme for valget af lokaliteter baseret på ES. Denne ramme tager afsæt i MSP-SA, der anvendes til muslingeopdræt. Gennem det sidste bidrag viser afhandlingen, at ES konceptet kan bruges til at strukturere planlægningsprocessen, ved at hjælpe med at definere en normativ vision og strategiske mål, og ved at anvende en ES vurdering i driftsfasen. Desuden illustrerer planlægningsrammen, hvordan de forskellige bruger-miljø-modtager-interaktioner kan bruges til at bringe modstridende perspektiver og interesser på bordet.

Resultaterne fra denne ph.d. bidrager til en begrebsmæssig forståelse af forbindelserne mellem ES og MSP og giver adgangspunkter for interessenters inddragelse. Afhandlingen viser, at integrationen af ES i MSP gensidigt vil kunne forstærkes til fordel for begge – gennem fokus på de varer og tjenester, der skal leveres fra et planlægningsområde og vægten på fordele og modtagere af ES i planlægningsprocessen. Ph.d. projektet illustrerer endvidere, hvordan ES konceptet kan integrere valg af steder i MSP processen. På instrumentalt niveau giver afhandlingen værktøjer til at lette ES vurderinger gennem indikatorpuljen, GIS-egnethedsanalysen og "farm scale" modellen. Afhandlingen giver et udgangspunkt for anvendelse af ES konceptet i MSP praksis og anbefaler, at fremtidig forskning skal undersøge ES konceptets rolle for evaluering af eksisterende havplaner og til at udvikle et sammenhængende netværk af områder, der er vigtige for bevarelse af havmiljøet og menneskers livskvalitet.

PREFACE

I had not planned to pursue a PhD, but, at the same time, I have also discovered that my life does not follow plans regardless if I have one or not. So, when I finished my MSc, my firm plan was to stay in Denmark and to not (ever) go back to Germany. But then it so happened that I applied to this very interesting position at the Leibniz Institute for Baltic Sea Research in Warnemünde that just so happened to come along with a PhD position. When I was accepted at the position, I was reluctant – do I really want to move from lovely Odense to Rostock, in east (!) Germany (never say that you cannot have prejudices towards your own country)? More than three years later, I can only say that I am more than glad to have started this journey. It was challenging at times, but because of the support of so many people, it has been very rewarding (and Rostock became a home).

I would like to say thank you to the BONUS BASMATI partners. It was a pleasure working in the project, experiencing the support from many scientists, having enjoyable project meetings, and hearing encouraging words (e.g. enjoy your PhD life, afterwards it will only get worse). It was a very good start in the scientific world being part of such a large research project. I am very grateful to Henning Sten Hansen and Kerstin Schiele who accepted me as their PhD candidate. They provided me with invaluable support and time to figure out my research tracks. Many thanks go to Pia Frederiksen, Marie Maar as well as Janus Larsen and Karsten Dahl for welcoming me in Roskilde both in 2017 and in 2018. Thank you, Pia, for many discussions around ecosystem services, frameworks, classifications, and indicators. Thank you, Marie and Janus, for having introduced me to the FlexSem modelling world. Thank you also to Ida and Aurelija, my PhD fellows in the BASMATI project.

My time during the PhD would have been much harder without the support of my friends in Rostock and elsewhere. Johanna and Esther, I do not know what I would have done without your friendship and Happyland, thank you for keeping me sane. Lotta, thank you for all the morning coffees (and skype coffees when Corona hit), your positivity, and the daily soap stories from your aquarium. Thank you to my old friends in the west – Kora, you are the most loyal friend I know, thank you for that.

Lastly, thank you to my family. You had me started on the journey before I even know what a PhD was, with your unmeasurable and endless support regardless which turn I take in life. Without you, I would have never dreamed so big – and words cannot express how grateful I am to you.

Warnemünde, August 2020
Miriam von Thenen

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THESIS DETAILS

Papers[1] included in this thesis:

- **von Thenen, M.,** Frederiksen, P., Hansen, H.S., Schiele, K.S., 2020a. A structured indicator pool to operationalize expert-based ecosystem service assessments for marine spatial planning. Ocean Coast. Manag. 187, 105071.
- Frederiksen, P., Morf, A., **von Thenen, M.,** Armoskaite, A., Luhtala, H., Schiele, K.S., Strāķe, S., Hansen, H.S. Proposing an ecosystem services-based framework to assess sustainability impacts of maritime spatial plans (MSP-SA). Accepted (with minor revision) in Ocean Coast. Manag.
- **von Thenen, M.,** Maar, M., Hansen, H.S., Friedland, R., Schiele, K.S., 2020b. Applying a combined geospatial and farm scale model to identify suitable locations for mussel farming. Mar. Pollut. Bull. 156, 111254.
- **von Thenen, M.**, Hansen, H.S., Schiele, K.S. 2020c. SPACEA: A Custom-Made GIS Toolbox for Basic Marine Spatial Planning Analyses. In: Gervasi O. et al. (eds). ICCSA 2020. Lecture Notes in Computer Science 12252, 394-404.
- Maar, M., Larsen, J., **von Thenen, M.**, Dahl, K., 2020. Site-selection of mussel mitigation cultures in relation to efficient nutrient compensation of fish farming. Aquac. Environ. Interact. 12, 339-358.
- **von Thenen, M.**, Hansen, H.S., Schiele, K.S. A generalized marine planning framework for site selection based on ecosystem services. Submitted to Marine Policy.

Other contributions referred to but not included in the thesis:

- **von Thenen, M.**, Schiele, K.S., Frederiksen, P., Aigars, J., Pakalniete, K., Strāķe, S., Puriņa, I., Hansen, H.S., Schrøder, L., 2018. Proposal for an ecosystem service framework for assessment of impacts of planning alternatives in a MSP perspective. BONUS BASMATI Deliverable 4.1. bonusbasmati.eu

Conference presentations:

- **von Thenen M.**, Maar M., Schiele K.S., Hansen H.S., 2018. Modelling ecosystem services provided by mussel farms in the south-western Baltic Sea. *European ESP Conference 2018*. San Sebastián, Spain.
- **von Thenen M.**, Maar M., Hansen H.S., Schiele K.S., 2019. A GIS suitability analysis for selecting mussel farm sites in the south-western Baltic Sea. *Aquaculture Europe 19*. Berlin, Germany.
- **von Thenen M.**, Frederiksen P., Hansen H.S., Schiele K.S., 2019. An indicator pool to support ecosystem service assessments for marine planning and management. *ESP 10 World Conference*. Hannover, Germany.
- **von Thenen M.**, Maar M., Hansen H.S., Schiele K.S., 2020. SPACEA: a custom-made GIS toolbox for basic marine spatial planning analyses. *International Conference on Computational Science and Its Applications*. Online.

[1] In the thesis, the references to these papers are highlighted in italics.

CHAPTER 1. INTRODUCTION

> "It is a curious situation that the sea, from which life first arose should now be threatened by the activities of one form of that life. But the sea, though changed in a sinister way, will continue to exist; the threat is rather to life itself." Rachel Carlson, The Sea Around Us

The quote by Rachel Carson is foreboding, but it includes two aspects, which are essential to this PhD thesis. The sea has (always) played a role in human history, as a place providing food, as a gateway for exploration and discovery, as an inspiration for philosophy and art. The sea had seemed endless, in its vast dimensions but also in its capacity to provide living (food) resources and to take up wastes and pollutants (Roberts, 2003). That the sea is not endless began to dawn upon society in the last century (Roberts, 2003; Sloan, 2002; UNCED, 1992). At the same time, the 20th century saw an increase in marine exploration and exploitation because of technical developments and improvements (Thurstan et al., 2015). In order to regulate marine uses, rules and laws were put in place. The United Nations Convention of the Law of the Sea (UNCLOS) enacted in 1992 sets the overall rules for the use of the seas and their resources (UN, 1982). The International Maritime Organization, a UN agency, is responsible for a regulatory framework of shipping and prevention of pollution from ships (e.g. MARPOL[2]). International agreements have been reached to protect marine areas beyond countries' exclusive economic zones (EEZ), such as the Antarctic seas[3] and the currently developed legal instrument for the conservation and sustainable use of BBNJs[4]. In the European Union (EU), a range of policies and directives are targeted at or have relevance for the sea. These include the Common Fishery Policy (1380/2013: EC, 2013a), the Habitats Directive (92/43/EEC: EC, 1992), and the Marine Strategy Framework Directive (MSFD) (2008/56/EC: EC, 2008), to name but a few examples.

It is expected that the sea will play an increasingly important role in the pursuit of blue growth (EC, 2012a; Eikeset et al., 2018; Moffitt and Cajas-Cano, 2014). The 2030 Agenda[5] and the Food and Agriculture Organization (FAO) emphasize the role of fisheries and aquaculture to provide proteins for a growing human population (FAO, 2018), which is projected to reach 9.7 billion by 2050[6]. Blue energy, such as

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[2] The International Convention for the Prevention of Pollution from Ships, www.imo.org

[3] Commission for the Conservation of Antarctic Marine Living Resources, www.ccamlr.org

[4] Marine Biological Diversity of Areas Beyond National Jurisdiction, www.un.org/bbnj/

[5] The UN Sustainable Development Agenda, https://www.un.org/sustainabledevelopment/development-agenda/

[6] https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html

offshore wind, wave, and tidal energy, furthermore, plays a role in securing renewable energy production. It is estimated that around 30% of the electricity demand in the EU will be covered by offshore wind by 2050[7]. The development of existing and emerging marine uses, supported by blue growth initiatives, have and will put pressure on marine ecosystems, creating user-environment conflicts. The sea is also a place of user-user conflicts because available space is limited (Douvere, 2008). As a tool to avoid these conflicts and to create synergies, marine spatial planning (MSP) has come into focus. MSP aims at allocating marine uses over space and time, ideally within the carrying capacity of the marine ecosystems.

Rachel Carson predicts that not the sea will cease to exist, but its capacity to sustain human life if marine uses and their pressures are not managed sustainably. The sea is essential for providing goods and services to human well-being (Worm et al., 2006). These goods and services are important to life itself such as providing food or flood control (Arkema et al., 2013; Worm et al., 2006). On a higher level on Maslow's hierarchy of needs, the sea is also a place for recreation, a place of cultural heritage, and inspiration (Elliott et al., 2017; Maslow, 1943). These contributions to human well-being can be termed ecosystem services (ES), which is the second important concept to this thesis.

The ES concept is part of the ecosystem-based management (EBM[8]) approach to MSP that recognizes the importance of the goods and services provided by the sea to society (Ehler and Douvere, 2009). While the ES concept has proven to provide valuable information for MSP (Arkema et al., 2015; Guerry et al., 2012; Veidemane et al., 2017), there remain challenges for the integration of ES in MSP. These challenges relate to the complexity of ES classifications and the often technical nature of ES assessments, which can make them less accessible to stakeholders (Friedrich et al., 2020). Furthermore, it is difficult to measure marine ES because of data scarcity, spatial mismatches between areas of ES supply and use, and a three-dimensional use of the marine environment (Townsend et al., 2018). This thesis explores and aims at integrating ES into MSP on a conceptual level and by using one marine use – mussel farming – as an example to explore required data for quantifying ES and to investigate how the ES concept can support MSP site selection.

In the following sections, both concepts – MSP and ES – are described in more detail as well as the connection of mussel farming to MSP and ES. This description is

[7] https://ec.europa.eu/energy/topics/renewable-energy/onshore-and-offshore-wind_en

[8] There are other, often interchangeably used, terms for EBM, including ecosystem approach, ecosystem-based approach, and ecosystem-based management approach. In this thesis, EBM is used in line with Ehler and Douvere (2009) and is understood as inclusive of the other terms. At the same time, it is recognized that there can be differences in the meaning of the various terms (Kirkfeldt, 2019).

followed by an elaboration of the research objectives and the research questions that guide the thesis. Finally, an overview of the thesis structure and chapters is provided.

1.1. BACKGROUND AND STATE OF THE ART

1.1.1. MARINE SPATIAL PLANNING

MSP aims at allocating space to marine uses over time such that economic, social, and ecological objectives can be achieved (Ehler and Douvere, 2009). Spatial planning at sea is increasingly necessary because of the pursuit of blue growth and competition for space between traditional and emerging ocean uses. Initially, MSP was developed as a nature conservation measure in the Great Barrier Reef Marine Park in the 1970/80s (Hassan and Alam, 2019). In 2009, the IOC[9]-UNESCO published a step-by-step guide to MSP for EBM (Ehler and Douvere, 2009), and in 2014, it became a legal requirement for EU Member States to prepare marine plans because of the EU Maritime Spatial Planning Directive (MSP Directive) (2014/89/EU: EC, 2014a) (Figure 1-1). This development shows that MSP can encompass different aspects. In its most fundamental form, it is a zoning of the sea that sets aside zones for marine uses as well as marine protected areas (MPAs). The IOC-UNESCO understands MSP as a public process with a focus on how MSP can balance economic, social, and ecological objectives from different stakeholder groups. In the EU, MSP is a legal requirement, which makes MSP subject to sociopolitical decisions regarding agenda setting, objectives, and priorities (Flannery and McAteer, 2020). The MSP Directive, furthermore, marks a shift from an EBM-MSP to an integrated-use MSP, where nature conservation areas are just one among other uses and can be traded-off (Jones et al., 2016). The UN Decade for Ocean Science may yet again be a gateway for MSP to move beyond the integrated-use focus of the EU MSP Directive with a focus on the Sustainable Development Goals (MSP Forum, 2019a) (Figure 1-1).

[9] Intergovernmental Oceanographic Commission, http://www.unesco.org/new/en/natural-sciences/ioc-oceans/

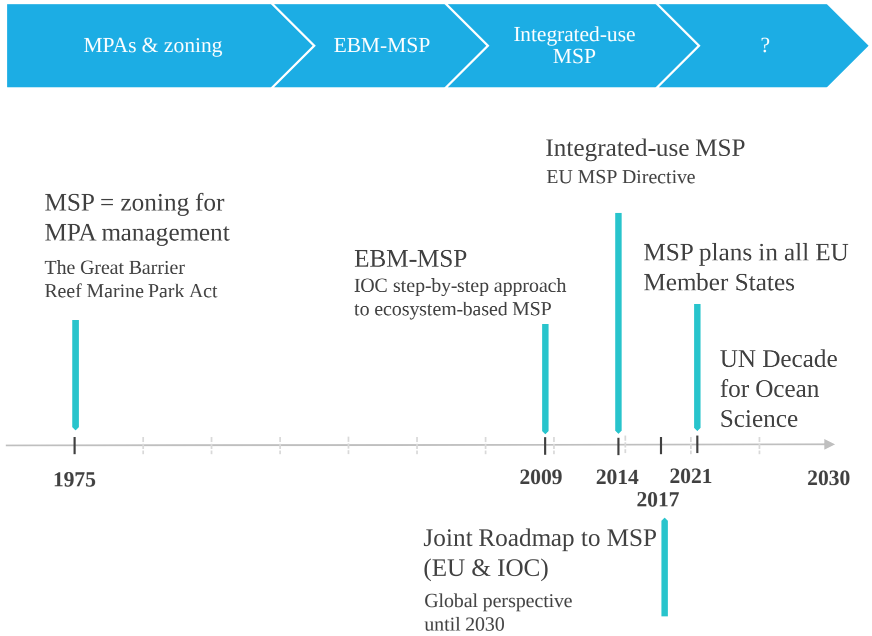

Figure 1-1: The development of MSP over time.

While there are different approaches to MSP, there are several aspects, which they have in common.

First, MSP is a *process*. The definition by the IOC-UNESCO refers to “a public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic, and social objectives that are usually specified through a political process” (Ehler and Douvere, 2009, p.18). VASAB[10] defines MSP as “a legally defined hierarchically process” (Ehler et al., 2019, p.6) with the aim to alleviate user conflicts. The MSP Directive highlights the role of public administrations to lead the MSP process so that human activities in sea areas are analyzed (EC, 2014a; Ehler et al., 2019). The common denominator of the definitions is the dynamic nature of MSP; it is not a static marine plan but an iterative and adaptive process, which results in a plan. However, even the resulting plans are not rigid because they are evaluated and adapted for the next planning cycle (Figure 1-2).

[10] Vision and Strategies around the Baltic Sea – an intergovernmental multilateral cooperation of Baltic Sea countries (vasab.org).

Second, MSP is a *participatory* process that should involve stakeholders from the very beginning. MSP is a form of governance that depends on public choice and democratic decision-making (Ehler et al., 2019). The realization of stakeholder participation in MSP largely depends on political will, resources, capacity, and time (Morf et al., 2019), both from the side of the planning team but also from the side of the stakeholders. Stakeholders can inform the MSP process in meaningful ways by providing insights to the spatial use of the sea, engaging in conflict resolution, and their involvement may support better compliance with the plans (Twomey and O'Mahony, 2019). The practice of stakeholder involvement, however, can vary greatly between countries and may not fulfil its promise of an open, transparent, and inclusive process (Morf et al., 2019; Twomey and O'Mahony, 2019).

Third, MSP is characterized by a *planning horizon* and the definition of a *planning area*. A typical planning horizon is 10 years (Gilliland and Laffoley, 2008), but some countries also have a planning cycle of only five to six years (e.g. Estonia, Belgium)[11]. A timeframe of 20 or more years, with cyclical review periods of 5-7 years, is another option (Gilliland and Laffoley, 2008). Furthermore, marine plans are spatially limited to specific sea areas. Space in the marine realm can be defined varyingly (Jay, 2012), but marine plans are usually delimited by administrative and jurisdictive boundaries. These boundaries can differ between countries; some countries have or are in the process of developing one main marine plan for their entire marine area (e.g. Poland), whereas others have a marine plan for the EEZ under federal authority and additional marine plans for the territorial seas under state authority (e.g. Germany). The degree to which the planning area also accounts for land-sea interactions – one guiding principle in the MSP Directive – also depends on the delimitations of the planning area and whether it includes the land-sea interphase.

Fourth, *data on existing and future conditions* in a planning area need to be collected and analyzed. Necessary data include the spatial and temporal distribution of human uses as well as the prevailing environmental conditions, such as oceanographic parameters and presence and distribution of key species and habitats (Stamoulis and Delevaux, 2015). The mapping of existing conditions in a baseline scenario is a fundamental requirement for MSP as well as an analysis of how marine uses should be located in the future with a focus on conflict avoidance and synergy creation. Ideally, alternative future scenarios should be developed, debated, and evaluated within the MSP process (Ehler and Douvere, 2009).

Thus, MSP consists of a series of iterating steps and an MSP cycle starts with organizing the process, which includes the organization of stakeholder involvement throughout the whole process, the development of visions and objectives, and the clarification of spatial delimitations and a time frame. In the next step, data needs to

[11] Maritime Spatial Planning Country Information – Estonia, Belgium, https://www.msp-platform.eu/msp-practice/countries

be collected and analyzed, which feed into the plan drafting that should be open for consultation and, ultimately, has to be approved and implemented. Monitoring and evaluation of the MSP plan present the last step of the cycle and, at the same time, can initiate the next round of the process (Figure 1-2).

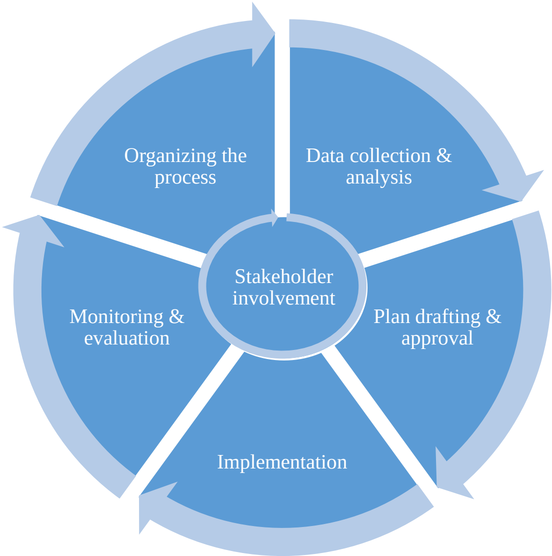

Figure 1-2: The MSP cycle. Adopted from Ehler and Douvere (2009) *and Giacometti et al. (forthcoming).*

In the EU, the MSP Directive requires the establishment of marine plans by March 2021 and is, therefore, a major key to understand how MSP is approached by Member States. The MSP Directive rests both on the MSFD and on the blue growth strategy (EC, 2012a) and may be seen as a bridge between these two under the umbrella of sustainable development (Hassler et al., 2019). However, the Directive does not provide any guidance on how to balance these, sometimes rather diverging, interests. This lack of guidance can lead to confusion about the main purpose of the Directive. Adding to the confusion are the different legal bases the Directive needs to draw from. As spatial planning in marine areas is not covered by the EU Treaty[12] (EC, 2012b), the MSP Directive draws on several legal bases that do fall within EU competences, such as fishing, transport, environment, and energy (Articles 43(2), 100(2), 192(1), and 194(1) of the EU Treaty, respectively, Westholm, 2018). At EU level, the implementation of the MSP Directive is placed under the Directorate General for Maritime Affairs and Fisheries (DG MARE), which is claimed to favor economic

[12] “This Treaty organises the functioning of the Union and determines the areas of, delimitation of, and arrangements for exercising its competences.” (EC, 2012b, p.50)

activities (Westholm, 2018). At the same time, one of its legal basis is environmental protection, which allows for a more "conservationist interpretation" of the Directive (Westholm, 2018).

The Directive, thus, leaves room for interpretation of its main purpose and, in addition, allows discretion for Member States for implementation according to their national laws because the MSP Directive is one of the new generation directives (Hassler et al., 2019). These directives are less strict with regard to compliance requirements and allow for greater flexibility in the transposition into national regulatory structures and institutions (Hassler et al., 2019).

A suitable area to study the different interpretations of the Directive is the Baltic Sea Region (BSR). It is one of the eight marine regions, mentioned in the MSFD (to which the MSP Directive refers) (Westholm, 2018), and it is often considered as the pioneer in MSP internationally. The diverging implementation and interpretation of the Directive among Baltic Sea countries highlight challenges such as the realization of transboundary cooperation and the EBM approach. The former can be hampered by competent authorities at different scales and with different foci. In the Baltic Sea, half of the countries have assigned the competence for implementing the Directive under environmental ministries, while the other half placed the responsibility with a ministry focused on economic growth (Westholm, 2018). Westholm (2018), furthermore, criticizes that the MSP Directive did little if anything at all to clarify the concept of EBM. While the Directive mentions it several times, it does not explain how it should be approached or implemented. This lack of clarification has led to varying adoptions of EBM around the Baltic Sea, which, in parts, can also be explained with the different competent authorities as a ministry of environment, charged with the implementation of the Directive, arguably will put a stronger focus on EBM than a ministry of finance (Westholm, 2018).

In the Baltic Sea, clarification of the guiding principles and platforms for transboundary cooperation is to some extent realized through regional and sea-basin initiatives. The Helsinki Convention (HELCOM) through its Baltic Sea Action Plan (BSAP) plays an important role in guiding environmental protection, while the HELCOM-VASAB MSP Working Group promotes the development and coordination of national MSP in the BSR (Hassler et al., 2019). Informal MSP processes and consideration of transboundary cooperation in the BSR, furthermore, have taken place through various EU projects. Some projects are mainly research-based (e.g. BalticLINes[13], BalticRIM[14], BONUS BASMATI[15]), while others directly cooperate with the national planners (Baltic Scope[16], Pan Baltic Scope[17]). These projects provide a platform for an informal exchange between stakeholders (Morf et al., 2019). At an international level, the UNESCO's IOC and DG MARE are developing a guideline for MSP with a special focus on the implementation of transboundary MSP (Friess and Grémaud-Colombier, 2019).

The understanding of MSP has developed throughout the thesis but from the start, the focus was on the EBM approach to MSP. In this approach, the carrying capacity of ecosystems and the capacity of marine ecosystems to provide goods and services to society is included (Ehler and Douvere, 2009). EBM can be defined varyingly and can include different principles and criteria (Kirkfeldt, 2019). EBM criteria pertaining to ES can be explicit, e.g. ecosystem goods and services (Arkema et al., 2006), or implicit, e.g. coupled-social ecological systems (Long et al., 2015). Ecosystem goods and services are mentioned in the BSAP (HELCOM, 2007) and are part of the new "green infrastructure" concept for MSP (Ruskule et al., 2019). In the BSR, the consideration of ES in MSP plans has, however, only been attempted by Latvia (Veidemane et al., 2017) and Sweden (Karlsson, 2019).

1.1.2. ECOSYSTEM SERVICES

The concept of ES is not a new phenomenon. The first notion of ES can be dated back as early as 1949 to the American author, scientists, philosopher, and environmentalist Aldo Leopold (Haines-Young and Potschin, 2010a). In his Sand County Almanac, he, among others, mentions that "the chance to find a pasque-flower is a right as inalienable as free speech" (Leopold, 1949, p.vii) and ventures, e.g.: "That land yields a cultural harvest is a fact long known" (Leopold, 1949, p.ix). It reveals that the ES concept is rooted in the belief that nature is integral to human well-being. This notion is reinforced by the very first mentioning of the term "ecosystem services" in the book "extinction: the causes and consequences of the disappearance of species" by Ehrlich and Ehrlich, around 30 years later (West, 2015). It was, however, not until 2005 that the first worldwide assessment of ES and the implications ecosystem change has for human well-being was published (MEA, 2005). This Millennium Ecosystem Assessment (MEA) defines ES as the "benefits people derive from ecosystems" and

[13] Coherent Linear Infrastructures in Baltic Maritime Spatial Plans, https://vasab.org/project/balticlines/

[14] Baltic Sea Region Integrated Maritime Cultural Heritage Management, https://www.submariner-network.eu/balticrim

[15] Baltic Sea Maritime Spatial Planning for Sustainable Ecosystem Services, https://bonusbasmati.eu/

[16] Towards coherence and cross-border solutions in Baltic Maritime Spatial Plans, http://www.balticscope.eu/

[17] http://www.panbalticscope.eu/

distinguishes between four different classes of ES (supporting, regulating, provisioning, and cultural). The MEA drew worldwide attention to the ES concept and kick-started research in ES. The first study targeted at the impacts of biodiversity loss on ocean ES suggests severe implications for food security, water quality, and marine ecosystem stability if business as usual continues (Worm et al., 2006).

Since the MEA, the field of ES research has advanced quickly. Coming forth from the MEA, the focus was on economic valuation of ecosystems and biodiversity to make “nature’s values visible” and to quantify the costs of biodiversity degradation (TEEB, 2010). The Economics of Ecosystems & Biodiversity (TEEB) understands biodiversity as key to provide ES and differentiates between services and benefits. TEEB presents a modified classification of ES to avoid double counting, which was identified as a major drawback of the MEA classification (de Groot et al., 2010b). A classification of ES that can be used to translate between, e.g. TEEB and the MEA, is the Common International Classification of Ecosystem Services (CICES). CICES is now the most commonly used classification in Europe (La Notte et al., 2017) and defines, similar to TEEB, ES as the “contributions ecosystems make to human well-being” (Haines-Young and Potschin, 2010b).

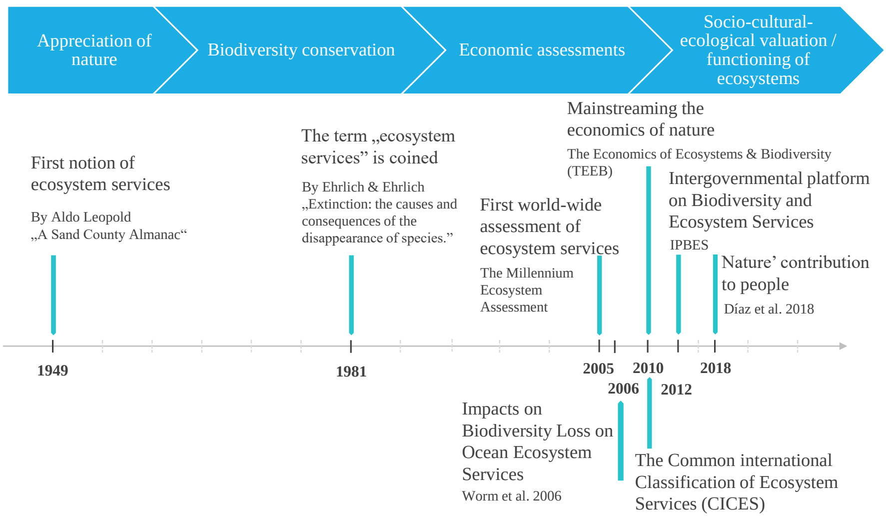

Figure 1-3: The development of the ES concept over time.

The ES concept is not without critique. One concern is that the ES concept leads to a capitalization of the natural world and in fact results in the commodification of nature (Dempsey and Robertson, 2012). A similar concern is raised by conservation biologists, who fear that the ES approach can lead to an unequal prioritization of only those ecological processes that in the end result in human benefits (Ingram et al., 2012).

A recent Science publication by Díaz et al. (2018), furthermore, raises the concern that indigenous knowledge is not sufficiently incorporated into the valuation of ES and suggests the term “nature’s contributions to people” (NCP). The NCP concept was developed by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES)[18]. Díaz et al.’s paper is controversially discussed by scholars (Braat, 2018; de Groot et al., 2018; Peterson et al., 2018) because of diverging views on whether IPBES ignores achievements of the ES concept and obliterates it or brings a broader perspective to it. This thesis understands the NCP as marking a potential transition to a broader understanding of the ES concept that is inclusive of both the western-dominated (economic) view and the ecological-cultural values of indigenous and marginalized groups (Figure 1-3). Furthermore, the functioning of ecosystems and how they can provide ES is (re)gaining attention (observation from the conference ESP, 2018).

The valuation of ES, which ideally should include economic, social, and ecological values (and combinations thereof, e.g. socio-economic, socio-ecological), justifies a PhD study on its own. Therefore, this PhD study did not attempt to provide a valuation of ES. Instead, the focus is on the ecosystem capacity to provide services and the benefits these services may provide to society. ES can be divided into three categories, following the CICES classification. They include the provisioning services (e.g. provision of food), the regulating and maintenance services (e.g. flood control), and cultural services (e.g. aesthetic enjoyment of land/seascapes). The generation of the ES depends on the interaction of ecological structures, processes, and ecosystem characteristics. Wetlands, for example, are capable of slowing down surface waters and can provide a “flood protection” service (Haines-Young and Potschin, 2010a). However, it can only be considered an ES if it provides a benefit to society, e.g. by protecting lives and property. This flow of ES from the environmental system to the socio-economic system is conceptualized in the ecosystem cascade (Haines-Young and Potschin, 2010a) (Figure 1-4). The ecosystem cascade understands ES as stemming from an interaction of ecological structures, processes, and ecosystem characteristics. The ES link these processes and functions to the benefits and values humans receive from ecosystems.

[18] https://ipbes.net/

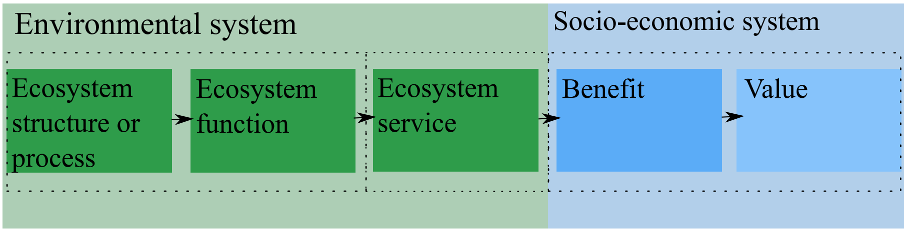

Figure 1-4: The ecosystem cascade. Adopted from Liquete et al. (2013) and Potschin-Young et al. (2018).

The ecosystem cascade as a conceptual framework can support ES mapping and assessments in the fields of environmental management and planning as well as decision-making (Baró et al., 2016; Böhnke-Henrichs et al., 2013). ES mapping in the terrestrial realm relies mainly on land use and land cover (LULC) maps (Burkhard et al., 2012). These maps provide a basis for assessing which land types can offer or provide ES. Such assessments are typically carried out with expert judgements in the so-called matrix approach, where each combination of LULC class and ES receives a score pertaining to the capacity of the land type to provide the respective ES (Jacobs et al., 2015).

ES assessments in the marine realm cannot rely on LULC maps and similar spatial datasets (e.g. marine habitat maps) are scarce (Townsend et al., 2018). Furthermore, “space” is inherently different in the marine environment. It not only includes habitat structures at the sea bottom but also the water column. Marine ES, thus, can rely on structures and processes in three dimensions, and because of the movement of marine waters, they can hardly be constrained to one spatial grid cell (Townsend et al., 2018). In addition, the areas where marine ES are generated and where the benefits are received often reveal spatial mismatches (Townsend et al., 2018). Marine ES, the ecosystem capacity to produce them, and where their benefits are realized, are, thus, inherently different from terrestrial ES. The ES concept, however, was developed considering land ecosystems, and, therefore, the used terminology needs to be adapted to the marine environment (Liquete et al., 2013). The latest version of the CICES classification (V5.1) indicates which ES apply to the marine environment without, however, providing marine-specific examples. ES assessments in the marine realm can use the matrix approach if the purpose is to evaluate the capacity of habitats to provide ES and if such data on habitats exist (Townsend et al., 2018). Other assessment methods include participatory mapping to elucidate where benefits are received (Klain and Chan, 2012) or by applying modelling tools to predict the supply of multiple ES (e.g. Guerry et al., 2012). ES assessments can be qualitative (e.g. by expert judgement) or quantitative. Quantitative assessments require the use of indicators because ES usually cannot be measured directly (Hattam et al., 2015).

Indicators are “proxies for complex phenomena” and can measure the supply of an ES (Hattam et al., 2015, p.63). The European Environment Agency (EEA), furthermore, highlights the role of indicators to simplify and by that to communicate real-world phenomena (EEA, 1999). The EEA understands indicators as reflective of a system's analysis view. This view is conceptualized in the Drivers-Pressures-State-Impact-Response framework (DPSIR). The DPSIR includes – similar to the ecosystem cascade – the environmental and human system. Social and economic Drivers put Pressures on the environment, which results in environmental State changes with Impacts on society. The impacts can induce a societal Response with regard to the drivers, pressures, or state changes (Figure 1-5). The DPSIR framework, in its present form, was developed by the EEA, which uses it for the analysis of environmental problems, but it has also gained traction in other areas, such as marine management (Elliott et al., 2017; Smith et al., 2016).

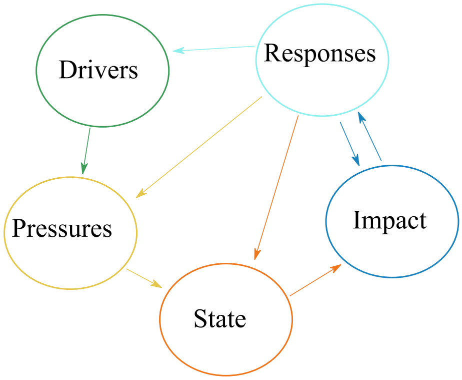

Figure 1-5: The DPSIR framework for environmental impact assessments. Adopted from the EEA (1999) and GRID-Arendal and UNEP (2016).

Both the DPSIR framework and the ecosystem cascade conceptualize the links between the environment and society or human well-being. The similarities between the frameworks are apparent, and in the literature, several examples and adaptations of a coupled DPSIR-cascade exist (Atkins et al., 2011; Dolbeth et al., 2016; Elliott et al., 2017; Kelble et al., 2013). Müller and Burkhard (2012) provide an example that integrates the cascade between the State and Impact steps of the DPSIR. This conceptualization is used as a departure point in this thesis for the consideration of the relationships between ES and MSP.

1.1.3. MUSSEL FARMING IN RELATION TO MSP AND ES

In this thesis, the integration of ES into MSP is considered on a conceptual level, whereas the generation of data in relation to ES is focusing on one (emerging) branch of aquaculture, namely mussel farming. MSP is mentioned as part of the EU's strategic guideline for aquaculture in order to ensure appropriate allocation of space for sustainable aquaculture (EC, 2013b). The FAO also advocates spatial planning for aquaculture. The FAO's ecosystem approach to aquaculture, furthermore, postulates that aquaculture should be developed considering ecosystem functions and services (Aguilar-Manjarrez et al., 2017). Aquaculture itself is treated as one provisioning ES in CICES and, in particular, bivalve farming can offer a range of other goods and services, including regulating and cultural ES (Olivier et al., 2018).

In the Baltic Sea, aquaculture practices include finfish and mussel farming (HELCOM, 2018a). Finfish farming plays a larger role in terms of production and turnover (HELCOM, 2018a). Mussel farming on a commercial scale and for human consumption only takes place in the western Baltic Sea, e.g. Kiel Bay (Germany), Limfjord (Denmark), and on the Swedish west coast (Buer et al., 2020; Kotta et al., 2020; Minnhagen, 2017). However, mussel farming has come into focus as a mitigation tool for excess nutrient loading in the Baltic Sea (Nielsen et al., 2016; Petersen et al., 2014; Timmermann et al., 2019). The Baltic Sea is highly eutrophied because of the high riverine and land run-off from the agriculturally dominated catchment areas (HELCOM, 2018b). The enclosure of the Baltic Sea with little water exchange and a strong stratification aggravates the situation. The results are hypoxic areas (Carstensen et al., 2014). National and regional efforts have reduced the nutrient input to the Baltic Sea over the last decades (HELCOM, 2018a). However, the reduction has not (yet) resulted in an improvement of the environmental state of the Baltic Sea (HELCOM, 2018a). There is a lag in the response time because of internal nutrient loadings from decades of excess nutrient input (Carstensen et al., 2006; Petersen et al., 2019).

Therefore, internal marine measures for nutrient reduction in the Baltic Sea are proposed (Petersen et al., 2019). These include the cultivation of mussels, which are filter feeders. Their primary food source is phytoplankton and seston biomass, and when the mussels filter their food from the water, they can immobilize the ingested nutrients (Dame, 2011). When the mussels are harvested, the nutrients can be extracted from the sea (Nielsen et al., 2016). The nutrient removal capacity can be regarded as a regulating ES of mussel farming (Nielsen et al., 2016). The use of mussel farming as a mitigation measure, however, is not unambiguous because mussels produce faeces, which can enhance biodeposition beneath the farm and could result in localized eutrophication (e.g. Rose et al., 2012; Stadmark and Conley, 2011). A proper site selection for aquaculture, e.g. with the use of Geographical Information Systems (GIS), is, therefore, necessary to ensure that environmental impacts are minimized (Petersen et al., 2012) and biological requirements of the cultured species are met (Aguilar-Manjarrez et al., 2017). Considering mussel farming in MSP may, furthermore, be beneficial for such a small and emerging use (which mussel farming is in the Baltic Sea) and ensure fair competition (Ruskule et al., 2014).

1.2. RESEARCH OBJECTIVES

The objective of this thesis is to demonstrate how the ES concept can support and advance MSP. Based on the background provided above, the thesis assumes that an EBM approach to MSP should be prioritized over an integrated-use MSP. This approach includes that MSP decisions should take into account the capacity of ecosystems to provide goods and services and how society benefits from them. Incorporating ES assessments into MSP comes with a number of challenges, however. The thesis aims at resolving three of these challenges. The first objective is to contribute to the clarification of the ES concept and how it can support MSP analyses. The second objective is to explore, with the example of an emerging ocean use (mussel farming), what kind of data and methods can be used to estimate ES. The third objective is to investigate how ES can contribute to MSP site selection.

1.3. RESEARCH QUESTIONS

The thesis is structured into three research questions based on the research objectives outlined above.

> *RQ1: How can existing ecosystem service frameworks be modified to facilitate the use of ecosystem services in marine spatial planning processes?*

The first research question aims at clarifying the ES concept for its use in MSP on a conceptual level. The thesis approaches RQ1 through a literature review and a conceptualization of the relation between ES and MSP.

> *RQ2: How can environmental data on biological, chemical, and physical parameters be transformed to provide the necessary information on ecosystem services in relation to aquaculture?*

The second research question deals with the lack of data and knowledge regarding the measurability of ES. This question moves from the generic to the specific level by using the example of mussel farming as one emerging use in the Baltic Sea. The thesis explores the data and methods that are needed for estimating the ES of mussel farming.

> *RQ3: How can a comparison based on ecosystem services support aquaculture site selection?*

The third research question explores an approach for basing site selection on the ES concept. The focus is on mussel farming, but the thesis also discusses the general applicability of the approach.

The research questions are answered through the four papers written during the PhD study. The additional co-author papers emerged during the PhD study and supplement the thesis by providing an additional or complementing perspective on the research questions. The next section describes the structure of the thesis and illustrates the connections between the different parts of the thesis, the research questions, and the papers (Figure 1-6).

1.4. STRUCTURE

The thesis consists of five chapters (Figure 1-6). The first chapter introduces the two main concepts of this thesis, MSP and ES, and outlines the research objectives and questions. The second chapter describes the methodology, which was partly informed by a BONUS BASMATI project deliverable (von Thenen et al., 2018). Chapter 3 comprises three sub-chapters, each providing a summary of the contributions with respect to the research questions. *Von Thenen et al.* (2020a) and *Frederiksen et al.* (accepted) contribute to RQ1 (ES for MSP); *von Thenen et al.* (2020b), *von Thenen et al.* (2020c), and *Maar et al.* (2020) to RQ2 (ES of mussel farming); *Maar et al.* (2020) also contribute to RQ3 (mussel farming site selection) along with *von Thenen et al.* (submitted). All the scientific papers are discussed in relation to the RQs, practical and theoretical contributions, and future research in Chapter 4. Chapter 5 concludes the thesis.

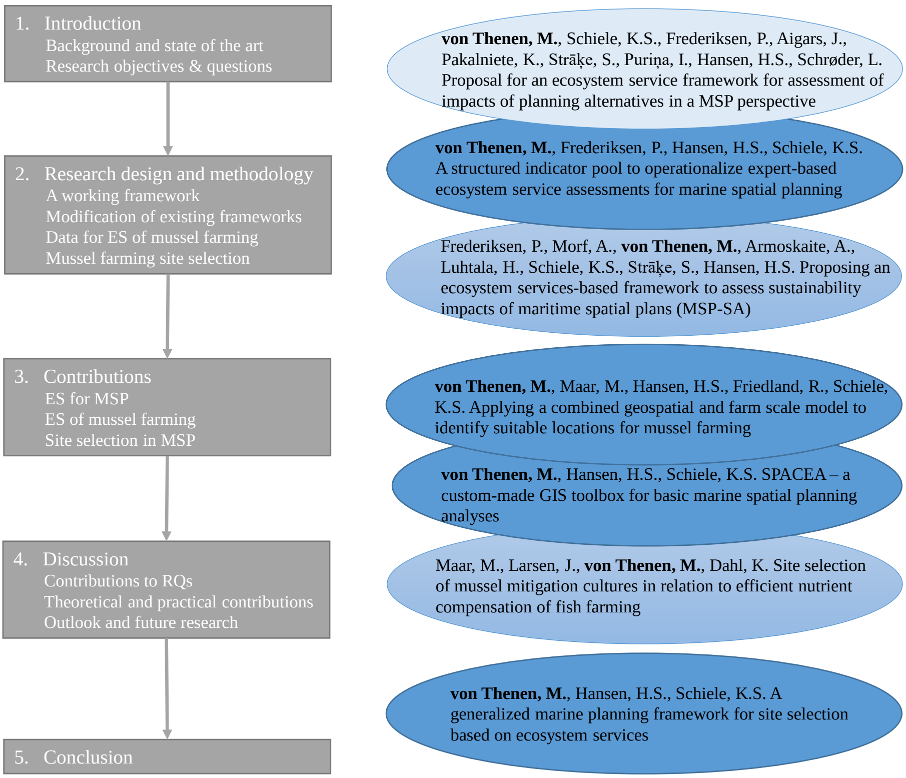

Figure 1-6: Structure of the PhD thesis and the contributions from the papers. Dark blue highlights primary contributions (first author), medium blue secondary contributions (co-author), and light blue the contribution from a project deliverable.

CHAPTER 2. RESEARCH DESIGN AND METHODOLOGY

This chapter presents the methods applied in the thesis. A working framework was used to explore the different research questions. For the first research question, data were collected through a scoping and literature review. For the second research question, data on marine uses and environmental conditions were collected from different databases and analyzed with GIS and an ecological model. For the last research question, all contributions were revisited in addition to data collected from two surveys that were analyzed with respect to different planning phases and further development of the working framework. Figure 2-1 depicts the overall research design applied in this thesis, which moved from a literature review to the operationalization of ES and conceptualization, to an in-depth analysis of data for ES of mussel farming, to a generalized marine planning framework for site selection based on ES.

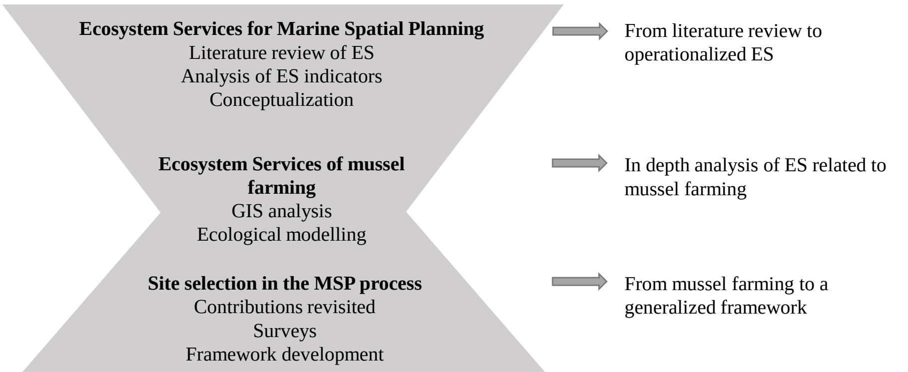

Figure 2-1: Overall research design and key methods applied in the thesis.

2.1. A WORKING FRAMEWORK FOR THE INTEGRATION OF ES IN MSP

The thesis departed in the coupled DPSIR-cascade proposed by Müller and Burkhard (2012). Two changes were made to this framework, which is presented in Figure 2-2, and were based on the following considerations. The DPSIR-cascade illustrates how drivers put pressure on marine ecosystems, which can adversely impact the provision of ES and derived benefits. Assuming that drivers can correspond to maritime activities (Hassellöv et al., 2015), it shows clearly how marine uses put pressure on the ecosystem. This conceptualization is useful for depicting those drivers that adversely affect ES; however, it fails to show the interdependencies between maritime activities and the ecosystem state. Some marine uses not only affect the marine environment negatively but may also provide benefits that depend on a functioning ecosystem state and the provision of related ES, e.g. mussel farming or recreational activities.

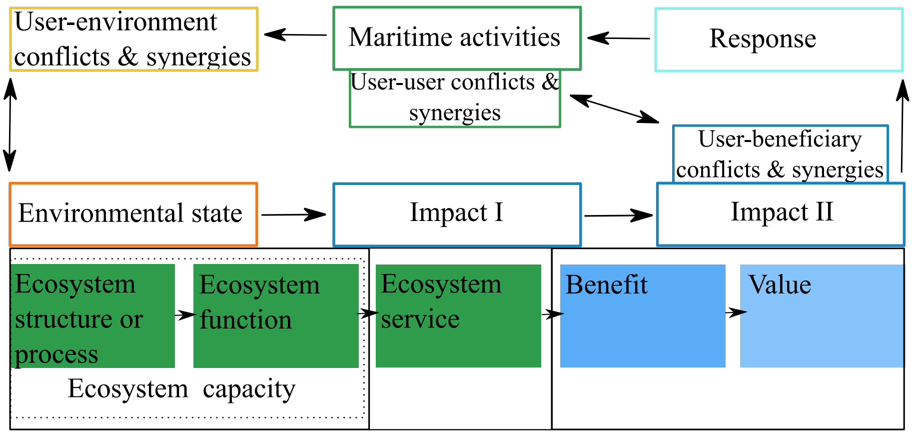

Figure 2-2: Working framework in which the thesis departed.

The first major change to the DPSIR-cascade, therefore, encompassed the replacement of the term pressure with the term user-environment conflicts and synergies. This change was inspired by the work of Douvere and Ehler (2009), who mention the user-user and user-environment conflicts within marine planning. The user-user conflict is apparent as marine uses can conflict with each other spatially and temporally. However, there can also be synergies between users, e.g. co-location between wind farms and MPAs (Christie et al., 2014). A second change included a third type of user-related conflicts and synergies (user-beneficiary) that was incorporated into the DPSIR-cascade. This notion of user-beneficiary interaction allows assessing the trade-offs between maritime activities and the beneficiaries of ES in one planning area.

The DPSIR-cascade presented a working conceptualization in this thesis to frame and guide the thesis' consideration of integrating ES in MSP. The focus of the thesis was to unfold the ES part of the DPSIR-cascade framework and to operationalize ES assessments within MSP.

2.2. MODIFICATION OF EXISTING ES FRAMEWORKS

The first research question aimed at clarifying the ES concept for its use in MSP on a conceptual level. The thesis approached this question through a scoping and systematic literature review, an analysis of how ES have been measured, and a conceptualization of the relation between ES and MSP.

In this thesis, an ES framework was defined as comprising a definition of ES, a classification, and a conceptualization. As shown in the state of the art, several definitions and classifications exist, and conceptualizations are based on them or combined and modified versions. The first step, therefore, was a scoping review of existing studies to obtain an overview of existing ES frameworks with a focus on marine ES and studies concerning the usage of the ES concept in marine management and planning (von Thenen et al., 2018). The MEA, CICES, and TEEB were identified as the three major classifications of ES at the time of the scoping review (October 2017). All three classifications (and combinations of them) are applied to the marine realm (Beaumont et al., 2007; Böhnke-Henrichs et al., 2013; Hattam et al., 2015; Lillebø et al., 2016). CICES and TEEB, furthermore, conceptualize ES within the ecosystem cascade (de Groot et al., 2010b; Haines-Young and Potschin, 2010a).

One aspect coming forth from the scoping review was the consideration of abiotic ecosystem components and their relation to ES. There are diverging perspectives on abiotic services (Hattam et al., 2015; van der Meulen et al., 2016), but in this thesis, they are considered important for MSP, following the argumentation by van Meulen et al. (2016). For MSP, the inclusion of abiotic services is advantageous because it allows one to draw a more holistic picture by including benefits derived from, for example, wave and tidal energy and sand and gravel deposits in the sea. CICES (V5.1) provides the only classification that formally includes abiotic ecosystem outputs. Therefore, CICES was selected as the framework that should be modified. CICES provides a hierarchical structure with different sections (provisioning, regulating and maintenance[19], and cultural services), divisions (e.g. biomass), groups (e.g. cultivated aquatic plants for nutrition, material, or energy), and classes (e.g. plants cultivated by in-situ aquaculture grown for nutritional purposes). The first version (V4.3) of CICES was already published in 2013 and was applied in marine case studies throughout Europe (e.g. Lillebø et al., 2016). The thesis started working on CICES V4.3 but switched to the latest version (V5.1) in 2018. The latest version is the result of extensive consultations and revisions. CICES, just as the other classifications, departed in terrestrial ES. The relevance of these to the marine environment is indicated in CICES V5.1, which also provides a classification of abiotic services (CICES *extended*). However, to make it truly marine some modifications were needed, including a selection of marine relevant ES and modifications of names and description to make the links to the marine environment explicit (*von Thenen et al., 2020a*).

The inclusion of abiotic services necessitated a modification of the ecosystem cascade. The ecosystem cascade was developed based on the idea that ES always stem from an interaction of ecological features and living processes. The original cascade distinguishes between biophysical structures and processes and ecological functions, where, in particular, the latter excludes abiotic services. In order to avoid having

[19] Hereafter, the regulating and maintenance services are abbreviated to regulating services.

different cascade steps for CICES *extended*, the two first cascade steps were merged into one, called ecosystem capacity (Figure 2-2) (*von Thenen et al., 2020a*) in line with (Baró et al., 2016; Liquete et al., 2013; Potschin-Young et al., 2018). The ecosystem capacity, furthermore, resembles more closely the environmental state in the DPSIR-cascade.

A systematic literature review was subsequently carried out to collect indicators for each step of the cascade at the level of the ES classes. Liquete et al. (2013) suggest that indicators are prerequisites for operationalizing ES. Existing indicators were collected and analyzed with respect to the different cascade steps. The analysis showed that some indicators are used interchangeably for the different cascade steps. Therefore, a thorough sorting technique was applied. Details are described in *von Thenen et al.* (2020a), which, furthermore, linked the cascade steps to MSP data requirements and the data analyses steps in MSP.

While the major contribution to this thesis was the operationalization of the ES part of the DPSIR-cascade, the thesis also contributed to developing the framework further. In a workshop, organized within the BONUS BASMATI project, the role of the ecosystem cascade in assessing planning areas was discussed and, in particular, the role of ES benefits and beneficiaries. The workshop contributed to the development of an impact assessment framework for MSP based on ES. The specific methods for further developing the framework are described in *Frederiksen et al.* (accepted).

2.3. DATA FOR ES OF MUSSEL FARMING

In order to investigate the second research question, mussel farming in the south-western Baltic Sea was used as an example. Both the topic (aquaculture) and the geographical area came forth from the BONUS BASMATI project, in which this thesis operated. As shown above (cf. 1.1.3), mussel farming can be considered as one marine use subject to MSP and, at the same time, provides ES and can affect the ecosystem. Therefore, mussel farming presented a suitable case to link MSP and ES. The collection and transformation of data in relation to ES of mussel farming was approached through the lens of mussel farm site selection. Allocating space or sites to marine uses is one essential task of MSP. Drawing the link between mussel farm site selection, the required data to perform the selection, and how this relates to ES, therefore, was seen as a suitable approach to collect and transform data needed to measure ES of mussel farming.

As a first step, it was determined which factors should be taken into account for finding potentially suitable sites for mussel farming in the south-western Baltic Sea. The Baltic Sea is a heavily used sea and spatial user-user conflicts can occur. Therefore, data on existing and planned marine uses was collected for this area. The data on marine uses were obtained from publically available databases (*von Thenen* *et al., 2020b*). Mussel farming, furthermore, depends on certain environmental conditions. In addition to the biological requirements of mussels, also some prerequisites for the farms were considered, including suitable depth and low current speeds, to avoid potential user-environment conflicts because of the deposition of mussel faeces. Details are specified in *von Thenen et al.* (2020b).

The data on environmental conditions and existing and planned marine uses were combined using a GIS suitability analysis. Each data layer formed a criterion in a Multi-Criteria-Analysis (MCA) to which a parameter-specific suitability function was fitted. For each criterion, a suitability function on a binary (0/1) or continuous scale (0-1) was identified, where "zero" indicated areas not suitable and "one" areas suitable for mussel farming. The data layers were combined using raster calculation and applying the geometric mean. The GIS suitability analysis is in detail described in *von Thenen et al.* (2020b). The GIS suitability analysis formed the basis for developing a toolbox that merged and adapted a range of standard ArcGIS tools to simplify such analyses. The toolbox is based on custom-made script tools, using the Python site package ArcPy. The design of the toolbox, called SPACEA ("**s**uitable s**pac**e in the s**ea**"), is described in detail in *von Thenen et al.* (2020c).

The suitability analysis applied to the south-western Baltic Sea showed where mussel farming could be possible, which, in this thesis, was regarded as providing information on the ecosystem capacity to sustain mussel farming. Based on the mapped potential areas for mussel farming, potential mussel farming sites were selected in a focus area in the Danish part of the south-western Baltic Sea (Hjelm Bay). The focus area was selected because two aquaculture companies had applied for fish farm permits in this Bay. Furthermore, the Danish government had adopted a law on "compensatory marine measures in the establishment or expansion of aquaculture" that was to implement the Compensatory Marine Measures Act and to include mussel farming as one such marine measure (Retsinformation, 2016).

In order to generate data on ES of mussel farming, mussel growth was estimated at the selected sites in the focus area. The indicators, used for providing data on ES, came forth from the findings of the first research question. Mussel growth was identified as the key indicator to supply ES related to mussel farming. The methods to quantify the ES included a dynamic energy budget (DEB) model integrated into a 3D farm scale model. Mussel growth through filtration of phytoplankton was modelled with the DEB model. The DEB theory was originally developed by Kooijman (Kooijman, 2000, 1986) and provides a quantitative framework, which dynamically describes energy flows and mass budgets in organisms. Marie Maar from Aarhus University provided the DEB model applied in this thesis. The DEB model was integrated into a 3D farm scale model using the FlexSem modelling framework, which is based on an unstructured computational mesh (Larsen et al., 2020). The model uses chlorophyll (Chl-a), salinity, temperature, and currents as input parameters to estimate mussel growth. The modelling results were analyzed with regard to potential harvestable biomass, nutrient removal, and impact on water transparency (*von Thenen et al., 2020b*). The analysis also included the mitigation potential of mussel farms with regard to fish farm waste.

In a secondary contribution to this thesis, site selection of mussel farms in relation to fish farms (as a potential co-location) was further investigated as well as parameters pertaining to the nutrient regulation service of mussels (*Maar et al., 2020*). The study linked the DEB model to a biogeochemical model in the FlexSem environment, which considered the locations of fish and mussel farms. The biogeochemical model included dissolved nutrients, several functional groups of phytoplankton, zooplankton, detritus, and oxygen and described, among other, processes of nutrient uptake and recycling. The pelagic model was coupled to a sediment biogeochemical model. Nutrients from the fish waste could be ingested by phytoplankton and supported primary production in the model. The DEB model, describing mussel growth, was coupled to the biogeochemical model through the uptake of phytoplankton, nutrient excretion, respiration, and deposition of faeces.

Several scenarios were run with different locations of the mussel farms that included changes in the direction towards the fish farm and changes with regard to the current speed and food fluxes. For each scenario, nutrient transport across different transects (coastal and open-water areas) was calculated. Furthermore, the impacts on nutrient concentration, primary production, and bottom oxygen by the mussel farm were estimated as well as the accumulation of organic matter, nutrient concentrations at the surface, and fluxes beneath the mussel farm. Both the positive impacts (nutrient removal, transport, Chl-a depletion, Secchi depth, denitrification) and the negative impacts (dissolved inorganic nitrogen concentration, sediment organic content, ammonium flux from the sediment, sediment oxygen consumption) were compared between the different mussel farm locations. The values of these parameters were normalized by the maximum value, resulting in ratios between 0 and 1 (*Maar et al., 2020*). A ratio of 1 indicated the highest impact (i.e. best performance) with regard to positive impacts and the lowest impact (i.e. best performance) with regard to negative impacts. In order to compare the positive and negative impacts in this way, the normalization for the negative impacts followed "1-value/max" (*Maar et al., 2020*). The different scenarios (i.e. different mussel farm sites) were compared based on their performance (poor = ratio<0.33; medium = ratio 0.33-0.66; best = ratio >0.66) with regard to the positive and negative impacts.

2.4. MUSSEL FARMING SITE SELECTION WITH ES

The previous section described how data on ES were collected and analyzed in this PhD thesis. It covered aspects of the two first cascade steps – the ecosystem capacity and ES. Comparing mussel farm sites with respect to the ecosystem capacity and the provision of ES can contribute to and support site selection. The ES' contribution to human well-being, however, is realized at the benefits step. Therefore, the last contribution investigated the (dis)benefits that people may receive or associate with mussel farming and how this can contribute to site selection as well. The thesis approached the data collection of benefits and impacts through a literature review and two surveys. The aim of the surveys was two-fold: to find out whether benefits and impacts could be related to underlying ES (thus approaching the cascade top-down) and if this approach could provide useful information for the planning process.

The review collected benefits and impacts of mussel farming from the literature, which was complemented by a first survey (*von Thenen et al., submitted*). The first survey was targeted at a selected group of researchers, familiar with aquaculture. The second survey was distributed online, an invitation and link to the survey were distributed via three mailing lists, and the link was posted on twitter, the BONUS project news website, and a blog ("Ocean Oculus"). The email lists were targeted at stakeholders with knowledge on ES, MSP, and the Baltic Sea. The aim was to reach different stakeholders (academia, governmental, NGO, fishery, tourism, aquaculture, and coastal residents) in different countries. However, it was clear that the selection with the email lists would return primarily responses from academia and governmental. The thesis condoned this unequal representativeness in the survey to receive more responses, and because the main aim was to analyze the survey responses with regard to the planning process.

The survey results were analyzed with respect to the different conflict and synergy types set out in the DPSIR-cascade working framework and different planning phases. The thesis drew upon the planning phases introduced by Ozbekhan (1969), which were related to the MSP planning steps by Quesada-Silva et al. (2019). They include the normative, strategic, and operational planning phases. The last contribution set the planning context in which a site comparison based on ES can take place and was the major contributor to the last research question. However, the other contributions were also analyzed with regard to how the information revealed in them could contribute to a site comparison based on ES.

CHAPTER 3. FINDINGS AND RESULTS

This chapter presents the scientific papers that contributed to the PhD thesis. The paper contributions are summarized in the following way. The aim of the paper within the PhD thesis is described. Then a short overview of the methods applied in the paper is provided, followed by a summary of the main results, and the major discussion points are outlined. Sub-chapter 3.1 presents the findings relating to RQ1: "*How can existing ecosystem service frameworks be modified to facilitate the use of ecosystem services in marine spatial planning processes?*" Sub-chapter 3.2 includes the contributions in relation to RQ2: "*How can environmental data on biological, chemical, and physical parameters be transformed to provide the necessary information on ecosystem services in relation to aquaculture?*" Sub-chapter 3.3 presents the contributions pertaining to RQ3: "*How can a comparison based on ecosystem services support aquaculture site selection?*" The last sub-chapter summarizes the main insights gained from the papers and the contributions to the research questions.

3.1. ECOSYSTEM SERVICES FOR MARINE SPATIAL PLANNING

This sub-chapter consists of two contributions. *Von Thenen et al.* (2020a) operationalize the cascade part of the DPSIR-cascade, whereas *Frederiksen et al.* (accepted) further develop the DPSIR-cascade focusing on social sustainability aspects in MSP processes and emphasize the role of benefits and beneficiaries of ES.

A structured indicator pool to operationalize expert-based ecosystem service assessments for marine spatial planning

<u>Miriam von Thenen</u>, Pia Frederiksen, Henning Sten Hansen, Kerstin S. Schiele, published in Ocean & Coastal Management in April 2020.

The aim of this paper within the PhD thesis was to operationalize the cascade part of the DPSIR-cascade working framework.

The paper presents CICES as the ES classification relevant for MSP. To operationalize the ES, a literature review was performed to collect indicators at the level of the ES class. The indicators were structured with the ecosystem cascade. The first two steps of the cascade were merged into the ecosystem capacity to generate ES, which provide benefits to society and can be valued. The different cascade steps were connected to the MSP planning process and data requirements.

The first part of the results in v*on Thenen et al.* (2020a) presents the list of marine ES, stemming from biotic and abiotic ecosystem components, following the CICES structure. In total, 62 marine ES are on this list, which range from living marine resources for human consumption to coastal and marine water used as an energy source; from filtration services by marine organisms to dilution by marine ecosystems; and from whale watching opportunities to the presence of iconic seascape features (*Supplementary Information A, von Thenen et al., 2020a*). The marine ES are presented in the CICES terminology, which was adapted to emphasize the marine character. In addition, each ES is supplemented with either an example from the literature or examples provided by the authors in the case of less researched ES. A majority of the marine ES derive from living processes and only 19 from abiotic structures and processes. All ES categories are covered, 25 ES fall within the provisioning section, 22 in the regulating, and 15 in the cultural section.

In total, 772 indicators were collected from the literature, of which 735 were analyzed further and were sorted into the different cascade steps. The indicators form the basis of the indicator pool, an excel spreadsheet, that allows the user to filter the indicators based on the different hierarchical levels and codes from CICES, the cascade steps, and whether they belong to CICES (biotic ES classes) or CICES *extended* (abiotic ES classes). The indicator pool is the first of its kind that specifically includes ES that are provided by abiotic ecosystem components and processes. *Von Thenen et al.* (2020a) acknowledge that the idea of abiotic ES is ambiguously debated in the literature but, at the same time, emphasize that some biotic ES already include abiotic aspects and that a holistic approach should consider all goods and services derived from natural systems.

In the indicator pool, several criteria provide a first judgement of the indicator quality, and the indicators are aggregated under common themes. The indicator themes show which types of indicators are used for the different cascade steps and across the provisioning, regulating, and cultural ES. The themes reveal that some indicators are used to quantify a dis-service or dis-benefit. *Von Thenen et al.* (2020a), furthermore, show that a majority of the indicators refer to the economic value of the ES classes. For some of the ES, no indicators were found in the literature search. Many abiotic ES classes lack indicators as well as some ES classes in the provisioning and the regulating section. In addition, not all cascade steps are equally well covered by the indicators. Indicators for the ecosystem capacity to provide ES are least abundant and mainly cover the regulating section. Indicators for benefits and values are most strongly represented in the provisioning and cultural section. *Von Thenen et al.* (2020a) reveal that this uneven distribution of indicators across cascade steps can partly be explained by the different definitions of ES. Some classifications, such as the MEA, equate ES with benefits, and consequently, indicators representing a benefit are used to measure the ES.

The indicator pool structured with the cascade can provide useful information for an MSP process. *Von Thenen et al.* (2020a) illustrate how the cascade steps link to different steps in the MSP process and MSP data requirements. Two steps in the MSP process rely heavily on data collection and analyses. These include the analysis of existing and future conditions, i.e. stocktaking and scenario analyses. For the stocktaking, the cascade can be read bottom-up to assess which ecosystem components may provide ES, which ES are present in a planning area, and the importance of the derived benefits for society. When scenarios are developed, the cascade can be approached from a top-down perspective. Thus, the starting point would be the values that different stakeholder groups attach to a sea area, and from there, different scenarios could be developed to decide which benefits should be produced from the area and on which ES and ecosystem components the benefits rely. The role of the indicator pool, thereby, is to provide a structured overview of available indicators. Indicator collection and selection is one challenge for ES assessments, and a common starting point as presented with the indicator pool resolves planners and experts of this task.

Based on the indicator analysis, *von Thenen et al.* (2020a) advise that future research should be targeted at those ES classes that are less well studied. These include the ecosystems capacity to provide regulating and cultural ES as well as benefits derived from marine ES beyond fish or aquaculture harvest and economic valuation. *Von Thenen et al.* (2020a) show that some gaps can be filled by referring to related ES classes that depend on similar ecosystem components or processes. *Von Thenen et al.* (2020a) discuss that the indicator pool provides a suitable starting point for ES assessments if some limitations are recognized. The indicators for the different cascade steps should not be confounded for a direct linkage between the steps. The cascading effects of an ecosystem's capacity can vary in different areas, i.e. a certain habitat or species may provide a range of different benefits depending on local and geographical contexts. As a second limitation, *von Thenen et al.* (2020a) address the need to consider the ES alongside the received benefits because on its own the ES step only refers to the potential supply of ES. A third limitation refers to the need for human, built, and social capital to turn some ES into benefits, which is not included in the indicator pool.

Proposing an ecosystem services-based framework to assess sustainability impacts of maritime spatial plans (MSP-SA)

Pia Frederiksen, Andrea Morf, Miriam von Thenen, Aurelija Armoskaite, Hanna Luhtala, Kerstin S. Schiele, Solvita Strāķe, Henning Sten Hansen, accepted (with minor revisions) in Ocean & Coastal Management.

The aim of this paper within the PhD thesis was to explore the role the benefits and beneficiaries of ES can play in MSP; thus, approaching the ecosystem cascade from a top-down perspective.

The main methods applied in the paper include i) a document analysis of existing MSP plans and scenario development in the Baltic Sea countries and an interview with key planners ii) a document analysis of MSP plans from countries where social sustainability assessments had been carried out and iii) research on existing conceptual frameworks.

The different analyses carried out in *Frederiksen et al.* (accepted) resulted in the development of a sustainability assessment (SA) framework for MSP (MSP-SA). The MSP-SA departs in the DPSIR-cascade and presents a modified version of it, which implies the different user-environment-beneficiary interactions without naming them in the conceptualization. The drivers are equated with sea uses, which influence the ecosystem capacity through pressures, mitigation, or claim on sea space. The cascade part is divided into three impact categories. The first impact category corresponds to the ecosystem capacity, which can be positively or negatively influenced by marine uses. The second impact category comprises the ES, which can be changed because of the influences on the ecosystem capacity. The third impact category relates to the economic and social impacts on human well-being. The category includes the (dis-)benefits received from ES, which provide values that can be perceived in various ways by different groups, stakeholders, and communities. This category, furthermore, adds the distribution of (dis)benefits as an important social assessment category because the distribution can be quite different from a baseline scenario to future scenarios in terms of who receives the (dis)benefits. The potential beneficiaries of several provisioning, regulating, and cultural ES are provided, and *Frederiksen et al.* (accepted) highlight that all ES can provide benefits of social implication.

Frederiksen et al. (accepted) discuss that the MSP-SA does not have to be limited to marine areas but can be applied to land-sea interactions as well. Furthermore, the framework's duality in terms of its instrumental and conceptual role is highlighted. The MSP-SA can be used to carry out integrated assessments or to structure the involvement of experts and stakeholders in the planning process. Through the consideration of (dis)benefits and their distribution, it is expected that the MSP-SA can contribute to equity. However, *Frederiksen et al.* (accepted) also recognize that the power of such analytical tools and frameworks always depends on the facilitation, i.e. it is in the hand of the planners and decision-makers to promote equity in the process and outcomes. The (dis-)benefits, furthermore, cannot only have direct beneficiaries but can make secondary, tertiary, and more contributions. *Frederiksen et al.* (accepted), therefore, suggest that the interactions over space and time could be a valuable aspect of future research. *Frederiksen et al.* (accepted) also recognize that the MSP-SA framework is a first step. To reach its potential, it needs further assessment tools for pluralistic valuations, consideration of benefits not derived from ES (that can still have an impact on ES, however), and spatial information (over time) regarding the linkages between ES and benefits. Furthermore, there is no common or agreed method for social sustainability assessments in MSP, which has implications for cross-border cooperation and harmonization of methods. The same lack of harmonized methods applies to the monitoring and evaluation of MSP plans. While there is, thus, still much to be done to achieve (social) sustainability in MSP plans, the MSP-SA can be a first step as it addresses the importance of the social impacts from ES-derived benefits.

3.2. ECOSYSTEM SERVICES OF MUSSEL FARMING

This sub-chapter consists of three contributions. *Von Thenen et al.* (2020b) shed light on the ecosystem capacity to sustain mussel farming and quantify parameters, indicating ES (biomass, nutrient removal, water transparency). *Von Thenen et al.* (2020c) generalize the suitability analysis applied in *von Thenen et al.* (2020b) in a GIS toolbox. *Maar et al.* (2020) explore a potential user-user synergy between mussel and fish farms and a method to compare different mussel farming sites based on parameters, indicating regulating (dis-)services. The contributions approach ES indirectly through the lens of mussel farming site selection (cf. 2.3) and, therefore, present data and methods required to estimate ES without, however, referring to ES in the papers.

Applying a combined geospatial and farm scale model to identify suitable locations for mussel farming

Miriam von Thenen, Marie Maar, Henning Sten Hansen, René Friedland, Kerstin S. Schiele, published in Marine Pollution Bulletin in July 2020.

The aim of this paper within the PhD thesis was to collect, analyze, and generate data that could be used for providing information about ES of mussel farming.

The main methods comprised a GIS suitability analysis that combined data on environmental conditions and marine uses to identify potentially suitable areas for mussel farming in the south-western Baltic Sea. Within a focus area (Hjelm Bay), three sites indicated as suitable in the GIS analysis were further investigated in a farm scale model. The farm scale model consists of the DEB model that was integrated into a 3D farm model using the FlexSem framework. For both the GIS analysis and the farm scale model different scenarios were developed to show how uncertainties in the analyses could affect the results. The modelling, furthermore, was complemented with sensitivity analyses of the input parameters.

The first part of the results presents four maps of potentially suitable areas for mussel farming that came forth from the GIS suitability analysis. The four maps show the range from the least to the most restrictive suitability analysis. This range covers uncertainties with regard to environmental thresholds and status of marine uses. The maps show that only small parts of the case study area are suitable for mussel farming. The unsuitable areas include spatial restrictions, such as existing shipping routes and Natura 2000 areas, and insufficient environmental conditions, primarily low Chl-a levels and deep-water areas. In the focus area, additional restrictions include oxygen deficiency areas and the coastal zone buffer.

The farm scale model and sensitivity analyses applied to three sites in the focus area reveal that the mussel growth potential is mostly dependent on salinity and Chl-a. An increase in either parameter can to some extent compensate for a low value in the respective other parameter but not in combination with low temperature values. The site with, on average, higher levels of Chl-a and temperature shows the highest potential for mussel farming in terms of harvest. In addition to the sensitivity analyses, *von Thenen et al.* (2020b) apply four different scenarios to investigate the impact on mussel growth under changing farming conditions. The scenarios include a baseline, low winter temperatures, higher mussel densities within the farm, and elevated Chl-a levels. The scenario with low winter temperatures only results in small differences in mussel growth. The higher mussel densities show a decrease and the elevated Chl-a levels an increase in mussel growth. The scenario with elevated Chl-a levels is used to provide a rough estimate of the mussel farm's potential to compensate for a fish farm. *Von Thenen et al.* (2020b) show that one or several mussel farms of at least 65 ha to 124 ha would be needed to compensate for one fish farm with a net production of 2250 tons in the Hjelm Bay area.

Von Thenen et al. (2020b) show that mussel farms in the focus area would not be very efficient in removing nutrients, mostly because of low Chl-a levels. Despite the low Chl-a levels, the focus area, however, has still not reached a good environmental status. Therefore, *von Thenen et al.* (2020b) argue that mussel farms may still be employed in this area because they could increase water transparency, not just within the farm but also up to at least 200 m from the farm. *Von Thenen et al.* (2020b) emphasize that this increase could have positive cascading effects. The potential harvest from a single farm in the focus area is also low compared to other, highly eutrophic, areas in the Baltic Sea. The model suggests that shell length could reach suitable sizes after 2.5 years of production. While such mussels could be sold for human consumption (if a high quality can be ensured), *von Thenen et al.* (2020b) discuss that these mussels would be more suited for the production of feed or fertilizer.

One negative impact of mussel farming is also presented in *von Thenen et al.* (2020b). This impact refers to the deposition of faeces and pseudo-faeces in the sediment. To what extent this presents detrimental impacts or a potential food source for polychaetes is discussed. The farm scale model includes an estimate of the fecal production but does not link it to biochemical recycling in the sediment. *Von Thenen et al.* (2020b) argue that the incorporation of biodeposition estimates could be a future improvement of the model. Such an improved model could complement the estimates of nutrient removal and impact on water transparency. *Von Thenen et al.* (2020b) conclude that it is important for site selection to consider positive and negative effects of mussel farming, especially in eutrophic areas, and that the farm scale model can support the estimation of these effects.

SPACEA: a custom-made GIS toolbox for basic marine spatial planning analyses

Miriam von Thenen, Henning Sten Hansen, Kerstin S. Schiele, published in Lecture Notes in Computer Science in September 2020.

The paper was not planned from the onset of this PhD study but, instead, came forth from the GIS suitability analysis applied in *von Thenen et al.* (2020b). The toolbox generalizes the different steps in the GIS suitability analysis outlined in the previous paper and presents a method to estimate the ecosystem capacity of an area to sustain, e.g. mussel farming and related ES.

Existing ArcGIS functionalities were adapted and bundled in the toolbox. The toolbox is based on custom-made script tools written in ArcPy, which is a Python side package for ArcGIS. *Von Thenen et al.* (2020c) describe how aspects of user-friendliness and flexibility are included in the tools. User-friendliness is achieved by keeping user input to a minimum, providing clear documentation, and different access points for less and more experienced users. The toolbox is modular, i.e. the tools can be used independently from each other or step-wise if the purpose is a suitability analysis. Flexibility is also achieved by combining several functionalities within each tool. Among others, the tools can process multiple input layers at the same time, which was achieved by applying a multi-value parameter option in the scripts in combination with the zip() function from ArcPy.

Von Thenen et al. (2020c) describe the five tools from SPACEA and how they can be used for MSP analyses. The buffer-marine-uses tool allows the user to buffer several vector layers with various buffer distances at the same time. The tool can be used when different marine uses have various security zones and these zones need to be mapped. The raster-creation tool turns vector into raster layers taking into account the presence or absence of marine uses in the planning area, i.e. the resulting raster layer has values of 0 (presence of a marine use) and 1 (absence of a marine use), which follows the same logic as already outlined in *von Thenen et al.* (2020b). The environmental-thresholds tool can either be applied to mark areas that are suitable for a marine use based on prevailing environmental conditions or to indicate areas that are at risk, e.g. because of low oxygen levels. The suitability-function tool applies a linear continuous suitability curve to the input parameter. It can be used if an environmental parameter, such as current speed, is increasingly suitable for a marine use. Because the suitability-function tool can only consider increasing linear suitability, some pre-processing with the standard ArcGIS reclassify tool is necessary in cases where the suitability curve is different. The suitability-analysis tool can combine several raster layers using the geometric mean and can identify areas where a marine use may be preferentially located based on spatial availability and environmental suitability. In *von Thenen et al.* (2020c), the basic functionalities of the tools are outlined with an example, using Baltic-wide site selection for mussel farming. The example is provided for illustrative purposes only and, therefore, does not consider all the marine uses and environmental parameters as applied in *von Thenen et al.* (2020b).

Von Thenen et al. (2020c) discuss that SPACEA is suitable for providing fast analyses of the spatial availability and environmental suitability in a planning area. However, the toolbox does not require a certain quality or resolution of the input data. Therefore, the results are only as good as the quality of the respective input data. *Von Thenen et al.* (2020c), furthermore, remark on the different dimensions in the marine environment. SPACEA provides 2-dimensional analyses of the marine environment. The vertical dimension can be considered indirectly with the tools, e.g. when marine uses at the sea bottom, which do not conflict with uses at the surface, are excluded from the raster overlay. The temporal dimension can be considered by using input data from different seasons or by making assumptions about future changes. *Von Thenen et al.* (2020c), furthermore, propose that the importance of the different input layers could be incorporated in the future development of the suitability-analysis tool, in line with an MCA using weighted criteria. *Von Thenen et al.* (2020c) conclude that the toolbox offers important analyses for MSP in order to avoid conflicts and create synergies. At the same time, the tools are generic enough to be used for terrestrial planning as well, and, hence, they may provide important input to the management of both terrestrial and marine areas.

Site selection of mussel mitigation cultures in relation to efficient nutrient compensation of fish farming

Marie Maar, Janus Larsen, Miriam von Thenen, Karsten Dahl, published in Aquaculture Environment Interaction in August 2020.

The aim of this paper within the PhD thesis was to explore mussel farming site selection with regard to the location of a fish farm and a comparison of sites based on parameters indicating regulating (dis-)services.

The paper uses a fish farm in the Samsø Belt (inner Danish waters between Kattegat, Great Belt, and Little Belt) that was proposed by aquaculture producers as a case study. The paper applied the DEB model and a biogeochemical model coupled with the FlexSem framework. The fish farm waste and the transport was estimated as well as the uptake of phytoplankton by the mussels in several scenarios. Each scenario included a different location of the mussel farm. The different farm locations were compared, based on nutrient removal efficiency, environmental impacts on the water column, and benthic impacts.

Maar et al. (2020) show that one mussel farm (36 ha) can produce up to 2579 t-WW in the Samsø Belt within half a year and that nutrient removal increases with food flux up to a food flux saturation level of 0.70 mg Chl-a m^{-2} s^{-1}. The transport of nutrients is reduced in the scenarios with the fish and mussel farms as opposed to the scenario where only the fish farm is included. Compared to the baseline scenario (no fish or mussel farm), the mussel farms located in the coastal areas as well as two located in the open waters even result in less nutrient transport. *Maar et al.* (2020), furthermore, reveal spatial effects of a Chl-a decrease that extend over a large area, in particular, at the coastal farms. Dissolved inorganic nitrogen increases in the scenario where the mussel farm is located right next to the fish farm and also at two coastal farms. All farms show higher nitrogen and phosphorus sediment contents by the end of the year compared to the baseline scenario. The benthic negative impacts are highest in the scenario where the mussel and fish farm are co-located and at two coastal farms with very low bottom current speeds.

Maar et al. (2020) discuss the importance of the composition of the food flux and suggest that mussel growth can be stimulated more with a higher Chl-a level and a lower current velocity as opposed to a lower Chl-a level and a higher current velocity. A combination of lower salinity and lower food flux, furthermore, can explain the lower nutrient removal at some of the coastal farms. *Maar et al.* (2020) show that the one mussel farm could mitigate around 17-31% of the nutrients released by a fish farm with a production of 100 t-N. Some waste of the fish farm is likely transported along the bottom where mussel farms cannot compensate as they only remove nutrients in the surface waters when the rope culture is used (which is the case in Danish waters). However, most of the mussel farms could reduce nutrient transport to sensitive areas, such as sheltered bays or Natura 2000 areas.

Mussel farms can also have negative effects on both the water column and the benthos. The benthic impact is highest in the co-location scenario because of the combined effects of biodeposition from the fish and mussel farm. Considering all effects, the paper suggests that the mussel farms should be placed a few km away from the fish farm, either in coastal or open water areas and advises against direct co-location. It is also discussed that farm biomass and nutrient removal could be increased with different farming designs that can increase mussel abundance. *Maar et al.* (2020) compare all scenarios (different mussel farm locations with respect to the fish farm) based on changes in water quality and effects on the sediment. The mussel farming sites are evaluated based on their performance (good, medium, poor) with respect to the positive and negative effects. While the paper only considers these ecological effects of the mussel farm in the site comparison, it is also acknowledged that other marine uses would need to be taken into account in order to avoid potential (spatial) conflicts. *Maar et al.* (2020) conclude that models, such as the one applied in the paper, can be a suitable tool to provide data for the support of management decisions with regard to integrated aquaculture.

3.3. SITE SELECTION IN THE MSP PROCESS

This sub-chapter consists of one contribution. *Von Thenen et al.* (submitted) propose a framework for basing site selection on the ES concept.

A generalized marine planning framework for mussel farming site selection based on ecosystem services

Miriam von Thenen, Henning Sten Hansen, Kerstin S. Schiele, submitted to Marine Policy in July 2020.

The aim of this paper within the PhD thesis was to investigate whether benefits and impacts of mussel farming can be related to ES and how the ES concept can contribute to mussel farming site selection in the MSP process.

The development of the planning framework was informed by a literature review and two surveys. The literature review and the first survey were used to compile a list of the benefits and impacts of mussel farming. This list was linked to the underlying ES and was used in the second survey. The second survey investigated which of these benefits and impacts are associated with mussel farming, which ones are considered important for site selection, and whether they are considered important for the Baltic Sea. The survey results were analyzed with regard to the normative, strategic, and operational planning phases. This analysis served as a departure point for the planning framework, which rests on the MSP-SA (*Frederiksen et al., accepted*), the idea of ES beneficiaries, and the different conflict and synergy types present in the marine environment.

The first part of the results in *von Thenen et al.* (submitted) presents the benefits and impact of mussel farming that came forth from the literature review and the first survey. They are linked to the CICES classes and cover provisioning, regulating, and cultural ES. The beneficiaries range from coastal residents and tourists to mussel farmers, the marine environment, and society at large. In the second part, the results of the second survey are presented. The survey respondents selected the benefits “nutrient reduction” and “job opportunities” most often and, in total, fewer impacts than benefits. The most selected impacts are conflicts and deposition of faeces. The impact “diseases & non-natives”, furthermore, is considered important for site selection. The respondents could provide additional benefits and impacts they associated with mussel farming. Most of these benefits and impacts only reveal additional aspects rather than truly new benefits and impacts. Some of the new benefits and impacts are not related to underlying ES but rather address external barriers or drivers, which can be part of the MSP-SA.

The third part of the results describes the planning framework. For each benefit or impact, the potential user-environment-beneficiary interaction is indicated as well as relevant planning decisions. The planning decisions take place at different points in the planning process and may inform the development of a vision (normative phase), specific objectives (strategic phase), or aspects for site selection (operational phase). There are feedback loops between the strategic and operational phases to show that the area may not be suitable for achieving the objectives set out in the strategic phase. The planning framework was applied to the survey responses with relevance for the Baltic Sea. The paper summarizes the responses through the lens of the planning framework. The summary shows that there can be quite diverging perspectives on the benefits that should be produced from the mussel farm (strategic decision), on the areas that are suitable for producing the desired benefits (operational phase), and whether mussel farming in the Baltic Sea is economically viable and can contribute to nutrient reduction (operational phase).

Von Thenen et al. (submitted) discuss that the planning framework can be important, in particular, for areas where there are such diverging perspectives as in the Baltic Sea. It is emphasized that the operational phase requires the best available knowledge and science in order to assess which benefits and impacts can be expected in a planning area. *Von Thenen et al.* (submitted), furthermore, show that the ES class of bequest implies a normative vision (should the sea be used for mussel farming?) and could present the first potential barrier for establishing a mussel farm. The strategic phase addresses the question of which benefits should be produced from a mussel farm and which impacts should be avoided. Several user-environment-beneficiary conflicts can occur at this stage, but it also provides the opportunity to address misunderstandings (e.g. there cannot be an impact in terms of the spread of invasive species if only native species are farmed). *Von Thenen et al.* (submitted) discuss that the social perception of mussel farming is an important factor and suggest that the planning framework could increase social acceptance if relevant stakeholders are involved from the beginning. *Von Thenen et al.* (submitted) conclude that the marine planning framework can identify suitable locations for mussel farming and other uses based on a process focused on ES and related benefits.

3.4. SUMMARY OF MAIN FINDINGS

This sub-chapter summarizes the main findings from the papers and their contributions to the research questions. The main insights from *von Thenen et al.* (2020a) and *Frederiksen et al.* (accepted) with regard to RQ1 "*How can existing ecosystem service frameworks be modified to facilitate the use of ecosystem services in marine spatial planning processes?"* can be summarized as follows.

Von Thenen et al. (2020a) show that there is a range of existing ES frameworks with different definitions of ES. Some classifications have been applied to the marine environment, and recent discussions around abiotic services have resulted in their inclusion into the CICES classification. An overview with respect to marine ES based on the latest version of CICES was missing. The ecosystem cascade offers suitable links to MSP and may structure the stocktaking and scenario analyses in MSP.

Indicators are a prerequisite to quantify ES and the ecosystem cascade presents a useful frame to structure the wealth of existing indicators.

Frederiksen et al. (accepted) illustrate that frameworks can be conceptual or instrumental. Therefore, they can be used for structuring a process and/or for carrying out assessments. The (dis)benefits provided by provisioning, regulating, and cultural ES can all have social implications. Beneficiaries and distribution of benefits are important for considering the social impacts of MSP plans, and such considerations can be facilitated with the ES concept. Furthermore, the distribution of benefits may change, when new sea uses are introduced.

The following aspects are extracted from *von Thenen et al.* (2020a, 2020b, 2020c) and *Maar et al.* (2020) with regard to RQ2 "*How can environmental data on biological, chemical, and physical parameters be transformed to provide the necessary information on ecosystem services in relation to aquaculture?*"

Von Thenen et al. (2020a) contribute to RQ2 by providing a list of indicators, from which relevant ones for mussel farming could be chosen. In the CICES classification, mussel farming (i.e. aquaculture in general) is regarded as a provisioning ES. It is measured in terms of either biomass (ES), harvest (benefit), or sales and incomes (economic value). Indicators for the ecosystem capacity to provide ES of mussel farming are lacking in the indicator pool. From a Baltic Sea perspective, mussel farming may also contribute to nutrient removal, which is an indicator for the regulating ES class "filtration by marine organisms" (CICES code 2.1.1.2). Chl-a uptake can also be an indicator for the regulating ES. At the same time, water transparency is an indicator for the ecosystem capacity to provide a habitat service, and an improvement in water quality can indicate a benefit pertaining to cultural ES. Indicators are thus always context-specific. Some indicators, furthermore, are used to measure dis-services or dis-benefits.

Von Thenen et al. (2020b, 2020c) reveal that the potential for mussel farming and related ES depends on the environmental conditions at site. The ecosystem capacity to provide ES of mussel farming can be described by an interaction of different parameters. Salinity and Chl-a are important parameters for determining the ecosystem's capacity to sustain mussel farming. GIS offers a range of suitable functionalities to analyze and combine data on the marine environment. With respect to the DPSIR-cascade, GIS analyses can provide information about the ecosystem capacity and about user-user conflict/synergy potential. The former is achieved by combining data on different environmental parameters, which can provide estimates of the suitability of an area for a marine use as well as its capacity to provide ES. Ecological modelling as presented with the farm scale model can provide relevant information with regard to mussel growth, which determines the biomass production (provisioning ES), the nutrient removal potential and impact on water transparency (regulating ES). One potential dis-service of mussel farming is the production of faeces, which, if fully included in the model, can also be estimated with the model.

The following aspects are extracted from *Maar et al.* (2020). The potential for net nutrient reduction is confirmed even though the negative effects should not be ignored. Low bottom current speed is an important factor that increases benthic effects beneath a farm. High current speeds at the surface can increase the available food for mussels, although a high Chl-a level provides a higher contribution to the food flux. The two parameters are important for indicating the ecosystem capacity to sustain mussel farming as well as salinity. A combination of low salinity and low food flux decreases the ecosystem capacity to provide ES related to mussel farming. The nutrient removal cannot only be indicated with regard to a decrease in nutrients (by harvest) but also by a decrease in nutrient transport. Mussel farming can be used as a mitigation measure for fish farms; however, a direct co-location is not advisable. Therefore, it does not present a direct spatial user-user synergy, i.e. one area cannot be reserved for both farms; instead, the mussel farm would need space a few km away from the fish farm.

The main insights from *Frederiksen et al.* (accepted), *Maar et al.* (2020), and *von Thenen et al.* (submitted) can be summarized as follows with regard to RQ3 "*How can a comparison based on ecosystem services support aquaculture site selection?"*

Maar et al. (2020) compare different mussel farming sites based on parameters indicating regulating (dis-)services. *Frederiksen et al.* (accepted), furthermore, reveal that the (dis)benefits of a marine use are also important to consider and should be taken into account in the site selection. *Von Thenen et al.* (submitted) show that most benefits and impacts associated with mussel farming can be related to underlying ES and the others can be addressed within the MSP-SA. Asking stakeholders about the (dis)benefits they associate with mussel farming provides an additional, complementary, perspective and can be a starting point to develop a list of ES that should be assessed. The ES concept, furthermore, relates to normative, strategic, and operational planning phases and can frame a planning process, leading up to site selection.

The main findings are illustrated in Figure 3-1, which applies the MSP-SA to mussel farming (in an extended version, compared to Figure 1 in *von Thenen et al.* (submitted)). It depicts MSP as an enabler for allocating space to mussel farms based on the findings from *von Thenen et al.* (submitted). The mussel farms claim sea space, depend on, and influence the ecosystem capacity of an area. The ecosystem capacity can be described with several parameters, and the indicators for ES include biomass, nutrient removal, and Chl-a uptake. Impact a) and Impact b) are addressed in *von Thenen et al.* (2020b) and *Maar et al.* (2020), whereas Impact c) is addressed in *von Thenen et al.* (submitted). According to the findings from *von Thenen et al.* (2020a), the cascade part (Impact a to c) can be read bottom-up or top-down depending on the focus of the analysis (stocktaking vs. scenario analysis). The main methods applied in the thesis are highlighted in italics (Figure 3-1).

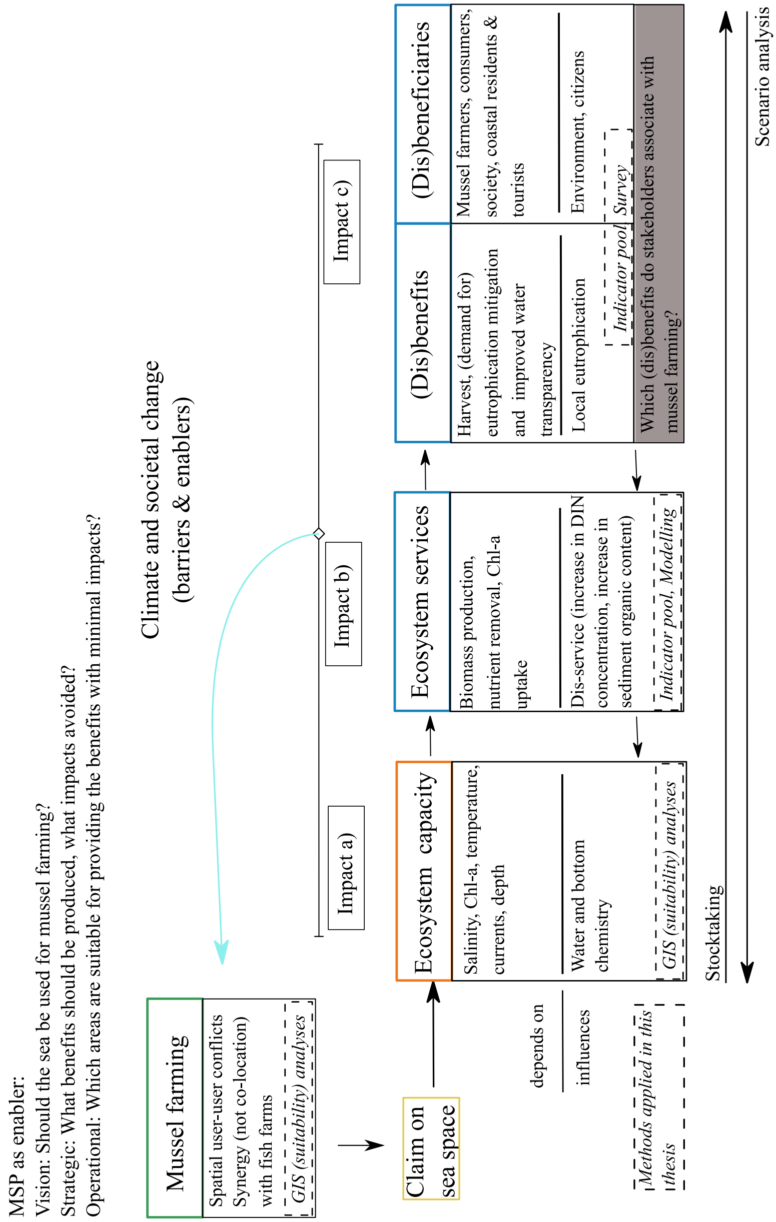

Figure 3-1: Overview of the main results of this thesis. The flow from ecosystem capacity to (dis)benefits is depicted based on the parameters quantified in the thesis. The list of (dis)benefits from von Thenen et al. (submitted) is not included, but the grey box indicates that the cascade can be approached starting at Impact c). DIN: dissolved inorganic nitrogen.

CHAPTER 4. DISCUSSION

This chapter discusses the findings of the scientific papers in light of the research questions and their theoretical and practical contributions. Future research is suggested, and a general outlook with regard to the expected future of ES in MSP is provided.

4.1. CONTRIBUTIONS TO THE RESEARCH QUESTIONS

RQ1: How can existing ecosystem service frameworks be modified to facilitate the use of ecosystem services in marine spatial planning processes?

The thesis focused on the modification of ES classifications and operationalization of the ES part of the DPSIR-cascade. Based on a literature review, the modifications included i) a selection and exemplification of marine ES ii) the inclusion of abiotic ES iii) a differentiation between cascade steps iv) collection of indicators for each cascade step and v) a conceptualization of the link between the cascade and MSP data requirements and analyses. In addition, the DPSIR-cascade was further developed to consider social sustainability aspects in MSP.

One finding of the literature review on existing classifications is that there are varying definitions of ES. While this is not per se a problem and can be explained by the different foci of the classification systems (e.g. economic accounting vs. nature's contributions), it results in different interpretations of the ES cascade. Either the different interpretations understand ES as part of the environmental system and the benefits derived from them as part of the socio-economic system, or they equate ES with benefits. The differences can have ramifications for ES assessments, in particular, when there are differences within one assessment with regard to how the different ES categories (provisioning, regulating, cultural) are treated. One example is the comparison of indicators belonging to different parts of the cascade, e.g. fish stocks as an indicator for a provisioning service and amount of beach visits as an indicator for a cultural service. Such a comparison would essentially equate the supply of ES with the use or demand of an ES, which is dangerous as it could lead to the assumption that there is an increase in cultural services over time. However, it only shows that the demand has increased but not the underlying capacity of the system to provide that ES (Hattam et al., 2015). Therefore, one important modification was the differentiation between the cascade steps and adoption of definitions for each. The thesis, furthermore, regards ES as part of the environmental system, which is in line with the CICES definition (Potschin-Young et al., 2018).

CICES applies a hierarchical structure to the ES. On the one hand, this structure is criticized for being very complex (Lillebø et al., 2016). On the other hand, the hierarchical structure allows the inclusion of additional ES if deemed necessary

(Czúcz et al., 2018). In CICES V5.1, abiotic services are included. One potential abiotic ES in the provisioning section was debated during the thesis and within the BONUS BASMATI project. This discussion evolved around space and whether it is i) an ecosystem attribute (belonging to ecosystem capacity) ii) an ES iii) a sense-of-place or iv) an abstract.

Space as an ecosystem attribute that provides a suitable substrate for human uses is, for example, described by de Groot (1987), who also refer to it as a carrier function with the premise that it often involves a long-lasting conversion of the ecosystem (de Groot, 2006). A carrier service is introduced by van der Meulen et al. (2016), who reflect on the role of rivers for transportation and the capacity of substrate to carry buildings. Viewing ocean space as a carrier service would allow considering wind parks and shipping lanes as a benefit of that service. Van der Meulen et al. (2016) also note that CICES refers, for example, to recreational boating as a cultural service. The cultural ES, furthermore, include aspects of sense-of-place. Sense-of-place describes the meaning and feelings people attach to different places (Massey, 1993). The cultural ES include characteristics and elements of (non-)living systems that provide meaning for people. Space in the sense of place, therefore, is covered by CICES.

Within the BONUS BASMATI project, space was considered as an abstract that can only be considered when a marine use occupies that space and potentially prevents the provision of other ES from that area. The thesis followed this argumentation and considered space as part of the conflict-synergy interactions in the DPSIR-cascade, which is translated to the marine uses' claim on sea space in the MSP-SA *(Frederiksen et al., accepted*). Thus, space is regarded as a physical entity, which becomes important when a marine use claims that space. However, the MSP-SA can address other meanings of space as well through the cultural ES and by considering the distribution of benefits.

The thesis provided a list of biotic and abiotic ES, which are described with examples *(von Thenen et al., 2020a*). This list was seen as a necessary step towards a clarification of the ES concept for MSP. The provided examples of each marine ES class show their diversity. Certainly, not all of them will be of relevance in a planning area, but it provides a starting point to obtain an overview of potential ES. ES, as provided on the list, can directly be assessed qualitatively. Expert-based assessments may rate to what extent marine ecosystems can provide each service, using a matrix approach (Townsend et al., 2018). The change of ES provision over time can also be qualitatively assessed by judging how much the provision has in- or decreased (Inácio et al., 2018).

The ambition of the thesis, however, was to also provide a starting point for quantitative ES assessments, which necessitated an operationalization of the ES, i.e. indicators. Reviewing existing indicators and indicator lists supported the earlier finding that the cascade is interpreted varyingly, and, hence, indicators are varyingly used for measuring the capacity, the ES, benefits, or values. The indicator pool (*von Thenen et al., 2020a*) allows navigating through the different cascade steps and presents a “pick and choose” for ES indicators. It can be regarded as a library of the most commonly used indicators. It provides filters, which make it easy to find appropriate indicators for different types of assessments. The filters, for example, include indicator themes, which refer to groups of similar indicators. *Von Thenen et al.* (2020a), thus, present a well-defined and sorted indicator pool that operationalizes the cascade part of the framework. It presents a departure point for ES assessments because the choice of indicators is an important first step (Hattam et al., 2015). The indicator pool as it is can be used for any marine-related ES assessment; it does not have a direct link to MSP, and the indicators only cover the cascade part of the DPSIR. However, it is illustrated how the cascade steps relate to MSP data requirements and can support and structure MSP data analyses, from stocktaking to scenario development (*von Thenen et al., 2020a*).

Scenario analysis is advocated as an essential part of MSP, ideally in co-development with relevant stakeholders (Ehler and Douvere, 2009). That the reality of planning practices is often different is revealed by *Frederiksen et al.* (accepted). Even in the MSP-pioneer region Baltic Sea, only a few countries (Finland, Latvia, Germany partly) have implemented scenarios in the development of their plans, and even fewer (Sweden, Latvia) have used ES assessments. ES assessments can support the development of scenarios and vice versa (Friedrich et al., 2020). The thesis proposed that a starting point could be to ask stakeholders about the benefits they receive or wish to receive from a planning area. Such an approach would put the beneficiaries central and can increase social sustainability. In the DPSIR-cascade working framework, the role of beneficiaries is indicated as user-beneficiary conflicts and synergies. It emphasizes that the users of marine areas may affect receivers of ES benefits negatively, for example, when a mussel farm disturbs the visual amenity service of a seascape. However, there can also be synergies, even with the same example – there might be people who enjoy the view of a mussel farm or on the long-term may benefit from an improvement in water quality.

Building on the working framework, *Frederiksen et al.* (accepted) developed an MSP sustainability appraisal framework. The notion of beneficiaries is retained in this MSP-SA, and the paper advocates the consideration of social sustainability in MSP plans. The different categories of ES are reflective of the three pillars of sustainability – people, planet, profit – or social (cultural ES), environmental (regulating ES), and economic (provisioning ES). In the EU, MSP plans with likely and significant negative effects on the environment have to undergo Strategic Environmental Assessments (SEA) as required by the SEA Directive (2001/42/EC: EC, 2001). In addition, Environmental Impact Assessments (EIA) are typically carried out for specific development projects (2014/52/EU: EC, 2014b) within the areas indicated in the MSP plan. Environmental sustainability, therefore, is addressed in MSP through the SEA and EIA. *Frederiksen et al.* (accepted) show that it is the social impacts that are not addressed. Cultural ES (which are the main contributors to the social aspects within the ES concept) are often under-valued; however, the ES concept can address social sustainability in several ways. The self-evident way is that the cultural ES relate to social benefits or impacts (if dis-benefits are received from the ES). However, understanding ES as a mixture of the ecosystem capacity that provides ES and the benefits individuals and society receive from these ES, entails a social dimension to all, i.e. provisioning, regulating, and cultural, ES. In essence, all ES can provide socio-economic, socio-ecological, or socio-cultural benefits and values.

The MSP-SA presents an approach to assess the impacts of marine uses on the ecosystems and the resulting impacts on beneficiaries. An application (and extension) of the MSP-SA to one marine use – mussel farming – is presented in this thesis. Within a planning area, there is likely a multitude of marine uses, which would need to be assessed in linked and nested versions of the MSP-SA. A linked and nested framework, also resting on DPSIR and ES, is applied in the DAPSI(W)R(M)[20] model (Elliott et al., 2017). The DAPSI(W)R(M) has a stronger focus on pressures and required measures, whereas the MSP-SA emphasizes the role of benefits and beneficiaries.

The consideration of beneficiaries is a timely contribution to MSP. Already in 2016, Flannery et al. (2016) argued for equitable and fair distribution of benefits received from the sea and for considering the question “cui bono?” (who benefits?) in MSP. The MSP-SA provides a framework that can address this question on both an instrumental and conceptual level. At the instrumental level, the assessment of ES and their benefits to society can be supported by the indicator pool *(von Thenen et al., 2020a*). In addition, the findings from RQ2 present a contribution to operationalize such assessments by exploring which data is needed for providing information on ES. At the conceptual level, the MSP-SA can facilitate the involvement of stakeholders in the MSP process (*Frederiksen et al., accepted*).

RQ2: How can environmental data on biological, chemical, and physical parameters be transformed to provide the necessary information on ecosystem services in relation to aquaculture?

As part of the framework development in response to RQ1, an answer to RQ2 is provided as well. In order to provide quantitative information on ES, indicators are necessary. The indicator pool, furthermore, shows that there is a distinction between the different steps of the cascade, and each step comes along with a different set of indicators. RQ2 was approached from the lens of mussel farm site selection; hence, the contributions also feed into RQ3 (cf. RQ3 discussion). The paper contributions to RQ2 do not mention ES but rather present the necessary data to estimate ES. Through

[20] DAPSI(W)R(M): **D**rivers-**A**ctivities-**P**ressures-**S**tate-**I**mpacts (on **W**elfare)-**R**esponses (as **M**easures)

this indirect approach, the thesis shows that essential data required to identify suitable sites for mussel farming is essentially the same data that is needed to quantify the ecosystem capacity and related ES. This finding confirms one result from *von Thenen et al.* (2020a), who show that the cascade steps relate to MSP data requirements.

Within the cascade, the biological, chemical, and physical parameters that should be transformed to provide information on ES in relation to aquaculture describe the ecosystem capacity. As described in the methods (2.3), the thesis focused on one specific form of aquaculture, i.e. mussel farming. Mussel farming presents a user-user conflict as well as synergy. At the same time, mussel farming can influence the marine environment positively and negatively (user-environment synergy and conflict).

The user-user conflict was approached with the GIS suitability analysis, which combined all marine uses in the south-western Baltic Sea that could restrict the establishment of a mussel farm. Not all of the uses necessarily constrain mussel farming (*von Thenen et al., 2020b*), and one potential user-user synergy was explored in more detail (see below). To estimate the ecosystem capacity to provide ES in relation to mussel farming, the GIS analysis **combined** environmental data on biological (Chl-a), chemical (oxygen), and physical (currents, bathymetry) parameters. The analysis, thereby, did not only account for the biological requirements of the species but also addressed a potential user-environment conflict. This conflict includes the accumulation of faeces in the sediment, and a minimum threshold for bottom currents was applied to alleviate this impact (*von Thenen et al., 2020b*). The thresholds and suitability functions were tailored to mussel farming in the Baltic Sea and are not universally applicable to other areas, species, or uses. However, the analyses behind it are suitable for a wide range of applications.

To facilitate a wider application of the suitability analysis, the GIS toolbox was developed. *Von Thenen et al.* (2020c) describe SPACEA as a toolbox for basic MSP analyses that can be used to process data on marine uses and environmental parameters and essentially to find “suitable space in the sea”. However, SPACEA can also be applied to gain a first impression of a planning area with regard to the present environmental conditions; thus, essentially the ecosystem capacity to provide ES. The ES may be related to one specific use as in this thesis. When the purpose is to identify the ecosystem capacity to provide any ES in a planning area, other data may be needed. The capacity to provide fish stocks may be dependent on nursery habitats. The capacity to provide flood protection is dependent on seascape features, such as natural sandbanks, and certain habitats, such as seagrass or coral reefs. The capacity to provide “enjoyment through passive or observational interactions” (CICES 3.1.1.2) may depend on suitable habitats and conditions for seabirds or marine mammals. SPACEA can be used to map the locations of habitats and to integrate them into the suitability analyses. However, SPACEA is (only) a tool; therefore, it does depend on the availability of adequate data. Furthermore, SPACEA can only indirectly consider vertical and temporal dimensions and variability. To address these dimensions directly, an area for future improvement could be to expand SPACEA and to include such variability more explicitly. The toolbox is not yet publically available; therefore, future work will also include the publication of SPACEA on GitHub[21].

The suitability analysis (and toolbox) combines different data, which may inform planners about the ecosystem capacity to provide certain ES. However, it cannot transform the environmental data to provide a quantification of ES. The quantification was approached through the farm scale model – the DEB model integrated into the FlexSem framework described in *von Thenen et al.* (2020b). The model also used biological, chemical, and physical input parameters. Unlike the GIS suitability analysis, however, the model **transformed** the data to provide estimates of mussel growth. In this thesis, mussel growth is regarded as the essential predictor of all ES that are directly related to the mussels (biomass, nutrient removal, Chl-a uptake).

The biomass can be used as an indicator for the provisioning ES. When the biomass is harvested, a range of benefits can be produced. The main benefit is the provision of seafood for human consumption. It is expected that a growing human population will increasingly rely on proteins from the sea (FAO, 2018), and mussel farming can contribute to the supply of proteins. In the Baltic Sea, however, not all areas are suitable for producing mussels for human consumption, mainly, because of the low salinity. Instead, the mussels may be used to produce feed or fertilizer (*von Thenen et al., 2020b*). In the Baltic Sea, the focus is on the regulating ES provision, i.e. the mussels' ability to remove nutrients from the sea. This nutrient regulation ES also depends on the capacity of the mussels to grow and, hence, primarily on environmental parameters such as the presence of phytoplankton and salinity.

The Chl-a uptake by the mussels is an ES that is present during the entire "farm-life" of the mussels. The farm scale model, furthermore, suggests that an increase in water transparency, through Chl-a uptake, can be seen at least 200 m from the farm *(von Thenen et al., 2020b*), and *Maar et al.* (2020) show an even wider-reaching effect. Chl-a uptake by mussels can be regarded as an indicator for the same CICES class to which nutrient removal belongs. However, the regulating ES of Chl-a removal is present when the mussel farm is operating, whereas the nutrient removal ES is realized when the mussels are removed from the sea. Therefore, both indicators are important to describe the regulating ES of mussels. Chl-a depletion, furthermore, can have positive cascading effects on other ecosystem components, such as macrophytes or seagrass (Nielsen et al., 2002; Thomsen et al., 2010). At the same time, an improvement in water transparency can be a benefit if there is a societal demand for good water quality, e.g. bathing water quality, in which case it can be regarded as an indicator for a cultural ES class. The case of Chl-a uptake by mussels, therefore,

[21] GitHub is an open source development platform to host and review software and codes, https://github.com/.

confirms the context-specificity of some indicators (*von Thenen et al., 2020a*) (cf. also RQ3 discussion).

The farm scale model was applied to a focus area in the south-western Baltic Sea, where two aquaculture producers had applied for fish farm permits. It presented an opportunity to investigate a potential user-user synergy between mussel and fish farms. However, the Danish government decided against the implementation of the Compensatory Marine Measures Act (cf. 2.3) in 2019, after, among others, a petition was brought before the European Parliament (European Parliament, 2017; Ministry of Environment and Food of Denmark, 2019). Therefore, the focus area had lost its actuality at a time when the thesis had already performed all the analyses. Nevertheless, it is expected that there will be an increase of finfish aquaculture in the future, which will necessitate some form of compensation measures, and, in particular, *Maar et al.* (2020) provide evidence that mussel farms can compensate for some of the fish farm waste.

Maar et al. (2020) also utilize the farm scale model but incorporate it into a biogeochemical model. This version considers the fish farm waste and includes the directions of flows, which is one drawback in *von Thenen et al.* (2020b). One important finding is that a direct co-location of the mussel and fish farms is not advisable when there are no lower trophic species, such as seaweed or sea cucumbers, that can mitigate the mussel faeces (*Maar et al., 2020*). The biodeposition beneath mussel farms is one potential dis-service; *Maar et al.* (2020) quantify the negative effects of mussel farms both in the water column and on the bottom. Along with the positive impacts on nutrient removal and transport, these parameters allow comparing different mussel farm sites. The parameters can be indicators for regulating (dis)services; hence, the results from *Maar et al.* (2020) also feed into the last research question.

The DEB model can provide estimates on other aquaculture species as well. Currently, DEB parameters exist for other bivalve species (e.g. European flat oyster, Peruvian scallop, Manila clam), crustaceans (e.g. European lobster, green tiger prawn, blue shrimp), and fish species (e.g. Atlantic salmon, rainbow trout, Atlantic cod) in the add_my_pet collection (van der Meer et al., 2014). A Web of Science search (July 3, 2020), furthermore, resulted in 55 hits, using the keywords “dynamic energy budget model” AND “aquaculture”. The DEB model, incorporated into the FlexSem modelling framework, thus, can be a suitable tool to estimate the ES related to aquaculture species and potentially also for other marine fauna.

The FlexSem modelling framework applied in this thesis, furthermore, can incorporate agent-based models (ABM). ABM can support the estimation of the ecosystem capacity to sustain mussel farming by predicting the distribution of mussel larvae (Pastor et al., 2019). The thesis assumed that larvae settlement would not be a restriction to mussel farming in the Hjelm Bay area (*von Thenen et al., 2020b*) because there are known mussel populations in the vicinity. Nevertheless, in other areas larvae settlement could be a restriction to mussel farming, and ABM can identify areas with sufficient or especially high larvae settlement.

The results from the DEB model applied in this thesis can be used to estimate the potential biomass, nutrient removal capacity, and water transparency impacts. These estimates include the most essential ES of mussel farming but not the full range of regulating and cultural ES that can potentially be provided by a mussel farm. One additional regulating ES includes the provision of habitat for other species. The artificial structures of the farm can provide a suitable substrate for other organisms, which can result in higher biodiversity surrounding the farms with positive cascading effects for recreational and commercial fisheries (Olivier et al., 2018). The mussels themselves can offer substrate for barnacles and are a food source for starfish and eider ducks (Minnhagen, 2017; Olivier et al., 2018). “Habitat provision” was included on the list of benefits used in the survey *(von Thenen et al., submitted*), and respondents selected it as a benefit they associated with mussel farming. At the same time, it can present a potential user-environment conflict with the mussel farmers, in particular, when predators are attracted. The thesis addressed this conflict by including the presence of eider ducks (the major mussel predator in the Baltic Sea) in the site selection of mussel farms (*von Thenen et al., 2020b*).

Another regulating ES that is potentially provided by mussels is carbon sequestration (Olivier et al., 2018). During shell production carbon is sequestered in the form of calcium carbonate; however, during the calcification process carbon dioxide is released (Olivier et al., 2018). Therefore, it is still debated whether mussels present a carbon sink or contribute to an increase in particulate CO_2 in surface waters (Olivier et al., 2018). The DEB model could provide a rough estimate of the carbon content in the mussels based on C:N:P ratios. However, it was deferred from including such estimation in the thesis as it is still debated if the mussels contribute to a net reduction of carbon in the sea, and it was not within the scope of the thesis to conduct in-situ measurements or experiments.

Cultural ES of mussel farming can include the opportunity for conducting research or educational activities linked to the mussel farm, for seafood festivals, or cultural heritage (Olivier et al., 2018). These ES are provided by the presence of the mussel farm in combination with activities on land. Essentially, the cultural ES also depend on the environmental parameters in the sense that they determine if mussel farming could be a viable option in the area. However, the ES can only be realized if there is additional social and human capital to transform the potential ES into benefits. The presence and size of the mussel farm can serve as an indicator for the ES but always has to be considered alongside the received benefits (*von Thenen et al., 2020a*). Cultural ES, furthermore, can be addressed in different phases of an MSP process (cf. RQ3 discussion).

RQ3: How can a comparison based on ecosystem services support aquaculture site selection?

When the research questions were composed at the beginning of the PhD study, the main idea behind RQ3 was that the ES concept could facilitate a better mussel farm site selection based on a comparison (and quantification) of ES. However, during the course of the thesis, RQ3 was reassessed – viewed in light of the contributions and their findings, which are revisited here.

Von Thenen et al. (2020a) provide a definition of ES and understand CICES' ES classes as consisting of the ecosystem capacity, the (supply of) ES, the benefits, and values. RQ3, therefore, cannot only be viewed in light of a comparison of ES but also with regard to the ecosystem capacity and benefits (and values; however, the thesis did not consider values, cf. 1.1.2). *Von Thenen et al.* (2020b, 2020c) provide a method and tool for comparing several areas with regard to their potential for mussel farming by looking at the ecosystem capacity. *Maar et al.* (2020) compare and rank several mussel farming sites based on parameters indicating regulating (dis)services. *Maar et al.* (2020) do not suggest which site is best or should be selected and emphasize that such a choice is up to the decision-maker. *Maar et al.* (2020) provide a scientific baseline for such decision-making; however, only the regulating dis(services) are taken into account because the focus is on the mussels' potential to mitigate fish farm waste. Nevertheless, estimates of biomass (as an indicator for the provisioning ES) could easily be implemented in the ranking of the mussel farm sites.

Coming from an estimation of the ecosystem capacity *(von Thenen et al., 2020b*) and quantification of parameters indicating ES *(Maar et al., 2020; von Thenen et al., 2020b*), the thesis moved from the environmental system to the socio-economic system with the last contribution (*von Thenen et al., submitted*). One finding from both *von Thenen et al.* (2020a) and *Frederiksen et al.* (accepted) is that an ES assessment within MSP may start by elucidating which benefits stakeholders receive from a planning area. Therefore, the thesis set out to investigate which benefits and impacts people associate with mussel farming, using two surveys. Some of the benefits used in the second survey relate to ES that can be quantified with the same indicators, e.g. Chl-a uptake as an indicator for improved water transparency or improved bathing water quality. The benefits, thus, can pertain to regulating or cultural ES and with input from stakeholders, it should be clarified which benefits are considered important and to which ES class they belong. Such a survey, as utilized in *von Thenen et al.* (submitted), thus, only presents a first step in determining the ES that should be considered in an assessment and does not (yet) require a clear-cut differentiation between the ES and benefit step. Approaching the cascade top-down, starting at the benefit step, reveals the importance of benefits attributed to mussel farming. It is a complementary perspective to the natural science view and can be a starting point for stakeholder involvement.

Von Thenen et al. (submitted) reveal that the ES concept, understood in a wider context, can inform a planning process also beyond the data collection and analysis steps in MSP. The paper proposes a marine planning framework for site selection, which was developed based on the survey results, and relates the ES concept to the different planning phases. The cultural ES of bequest (CICES code 3.2.2.2) is placed in the very beginning of the planning process by posing the question of whether the sea should be used for mussel farming at all. By linking it to the normative planning phase, it is clear that it is part of defining a vision for the planning area. CICES V5.1. describes the bequest service as the characteristics or qualities of species or ecosystems that people seek to preserve for future generations. In the survey presented in *von Thenen et al.* (submitted), this ES is framed with the question if farming in the marine environment is seen as a negative impact because the sea should remain in a natural state for future generations. Defining a vision for a planning area, thus, can be guided by questions such as: What should the sea be used for? Which species and habitats should be protected for future generations? And also which uses, goods, and services are necessary to sustain present and future generations? This vision can be translated into specific objectives for a planning area. The benefits and impacts, depending on underlying ES, that people (wish to) receive from the area can guide the formulation of these objectives (*von Thenen et al., submitted*).

The operational planning phase should include thorough data analysis and site selection. It is the phase where a quantitative ES assessment can take place. In a first step, the GIS suitability analysis (*von Thenen et al., 2020b, 2020c*) can be used to identify suitable areas in terms of spatial availability (user-user conflicts & synergies) and environmental suitability (user-environment conflicts & synergies), which provides an estimate of the ecosystem capacity. The indicator pool and the use of models, such as the DEB model, can support the quantification of ES, resulting from the ecosystem capacity. *Maar et al.* (2020), furthermore, show how parameters indicating regulating ES can be compared and evaluated.

Initially, the last contribution was planned to take place in form of a workshop, where planners, based on a pre-survey, were to discuss a case of mussel farming site selection based on benefits and impacts. The workshop was planned in cooperation with the BONUS OPTIMUS project, which in the end decided against any workshop. Potentially replacements within the BONUS BASMATI project were not possible because of the COVID-19 crisis. The thesis could have benefitted from applying both the MSP-SA and the adaptation to mussel farming in a real stakeholder setting. However, the thesis' findings do present a suitable starting point for practical implementation (cf. 4.2.2).

4.2. CONCEPTUAL AND PRACTICAL CONTRIBUTIONS

This sub-chapter discusses in which ways the thesis contributes to the conceptual, scientific, understanding of integrating ES into MSP and in which ways the thesis' findings can contribute to practical implementation.

4.2.1. CONCEPTUAL CONTRIBUTIONS

The objective of the first research question was to clarify the ES concept for its use in MSP on a conceptual level. This clarification involved the selection of one classification system and utilizing the ecosystem cascade for structuring indicators.

The ES concept is a fast-evolving research field, which also affected the thesis. The thesis started to work with CICES V3.4 and then had to switch to the latest version (V5.1). The indicator pool is the first of its kinds that rests on the latest version. Hence, it can be considered a timely contribution to CICES V5.1. The indicator pool provides a clarification of the different cascade steps, which is needed to make sound ES assessments. The thesis does not proclaim that the definition and applied differentiation between the cascade steps are universally applicable. The various definitions and understandings of ES reflect the diversity of the research field and are likely necessary to accommodate different types of ES assessments and the complexity of such socio-ecological systems (de Groot et al., 2010a). The thesis, however, emphasizes that ES researchers and practitioners should be aware that different interpretations of the cascade can affect the assessments. The indicator pool, thereby, provides a “pick and choose” library, which applies one definition of ES and provides one way of defining the cascade steps. Such a library will be helpful for ES researchers to gain an overview of existing indicators and will certainly prove useful for researchers starting to work with the ES concept.

The thesis also contributes to the understanding of the ES concept through its application to mussel farming. It offers several methods with which data on marine ES can be generated. Data on marine ES can be difficult to obtain, which is attributed to the marine environment that comes with challenges in measuring and generating data (Townsend et al., 2018). The ES concept was developed at land, where LULC maps (cf. 1.1.2) provide a basis for estimating the ecosystem capacity to produce ES (Burkhard et al., 2012). Similar maps may exist for the coastal zone and some well-researched marine areas. Through the application to mussel farming, this thesis shows that different data than habitat maps can be used for obtaining an overview of the ecosystem capacity – at least for certain ES. Species-specific models such as the DEB model, furthermore, can provide data for ES assessments.

The thesis, thus, contributes to an understanding of the ES concept. The thesis, furthermore, illustrates that both the ES concept and MSP have originated from a similar departure point (cf. 1.1), namely a focus on nature conservation, which over time has developed into a focus on economic valuation (ES concept) and blue growth (MSP). At the same time, there are parallels in recent developments: the recognition that information on ES needs to (or at least should) incorporate traditional and indigenous knowledge and values (e.g. Díaz et al., 2018); and that MSP should involve stakeholders in a considerate manner, paying attention to power imbalances and marginalized stakeholders (e.g Morf et al., 2019). MSP is a form of marine governance, in the EU even a legal requirement, and it depends on public choice mechanisms, necessitating some form of stakeholder involvement. ES assessments can be a tool to involve stakeholders and are mentioned by important MSP documents (EC, 2014a; Ehler and Douvere, 2009) but are not legally required. MSP and ES, therefore, could be mutually reinforcing for the benefit of both. The ES concept can be used to focus MSP processes and decision-making on the goods and services that should be produced from a planning area for the benefit of society; and MSP, having a higher legal binding[22], can implement ES as part of the planning process.

The thesis provides several, complementing, conceptualizations of the role ES can play in the MSP process. The DPSIR-cascade illustrates that marine use(r)s (after all the major planning subject of MSP) interact with the marine environment with implications for the ecosystem capacity to produce ES and the benefits provided to society. There can be a range of user-environment-beneficiary synergies and conflicts in the marine environment that should be addressed. These synergies and conflicts are exemplified for mussel farming by *von Thenen et al.* (submitted). An important aspect is that some marine uses, such as mussel farming, do not exclusively put pressure on the ecosystem state but can also influence the marine environment positively. The MSP-SA highlights, furthermore, the importance of considering the beneficiaries and distribution of benefits. *Frederiksen et al.* (accepted) suggest different ways of reading the framework, namely that it can be approached from the supply side (starting with the ecosystem capacity) or the demand side (starting from values attached to sea areas), which may structure MSP data analyses from stocktaking to scenario analysis (*von Thenen et al., 2020a*) and present entry points for stakeholder involvement. Furthermore, the conceptual MSP-SA framework shows that social sustainability aspects cannot only be approached through the assessment of cultural ES but also by considering the social implications of benefits derived from provisioning and regulating ES. On the one hand, the MSP-SA framework, thereby, contributes to the understanding of the ES concept. On the other hand, the MSP-SA is also a timely contribution to the call for addressing equity and distributional aspects in MSP (Bennett, 2018; Flannery et al., 2016; Kidd et al., 2020). *Von Thenen et al.* (submitted), furthermore, connect the ES concept to the different planning phases that are part of an MSP process.

4.2.2. PRACTICAL CONTRIBUTIONS

The thesis' research questions focused on the how: how can ES frameworks be modified? How can data on ES be generated? How can the ES concept support site selection? The main contributions, therefore, are conceptual. The application of the conceptual contributions (cf. 4.2.1) to "real-world" planning was not part of the PhD thesis. However, the thesis findings present a departure point for practical applications, which shall be outlined in this section.

[22] It is recognized that not all marine plans in the EU are legally binding. Nevertheless, the establishment of marine plans is a legal requirement in the EU.

Frederiksen et al. (accepted) show that the ES concept can address social sustainability of marine plans because all ES (provisioning, regulating, cultural) can have social implications. The MSP-SA, therefore, can provide an entry point for stakeholder involvement by highlighting in which ways people may benefit from the marine environment. Through the focus on beneficiaries, the MSP-SA can contribute to scenario development. For the stocktaking, the ecosystem capacity can be a departure point to assess which benefits are currently provided. For scenario development, the departure point is the beneficiaries, how they will be affected by new developments or future conditions (e.g. climate change) or by elucidating which benefits they would like to receive in the future. *Von Thenen et al.* (submitted), furthermore, show that the ES "bequest" can guide the development of a vision for a planning area by focusing on questions such as "what should the sea be used for?" (cf. 4.1). When the ES concept is approached from the benefit side, it is expected that it fosters a better understanding of ES and the ways ecosystems contribute to human well-being.

The thesis also contributes to practical implementation by offering tools for ES assessments. The indicator pool can be used to select relevant indicators for an ES assessment. Indicator selection is required to quantify ES, and a common indicator pool resolves planners and experts of the task to collect indicators *(von Thenen et al., 2020a*). The SPACEA toolbox facilitates a quick overview of a planning area and its ecosystem capacity. SPACEA is designed to be user-friendly and may also be applied by users with limited GIS knowledge. The farm scale model also facilitates the instrumental use of the ES concept and can be used to provide information on ES related to aquaculture species. Finally, *Maar et al.* (2020) provide a method to compare the provision of ES at different locations.

4.3. FUTURE RESEARCH AND OUTLOOK

The thesis investigated the integration of ES into MSP by focusing on establishing a framework, grounded in a thorough classification and operationalization of ES indicators, on data generation with regard to ES of mussel farming, and an approach for site selection based on ES. The thesis' topic presents a wealth of other research tracks, and at several points during the thesis, a different track could have been selected. The thesis could not follow these tracks, but they are presented here as potential future research topics.

In the first part of the thesis, the focus is on operationalizing the ecosystem cascade. The resulting indicator pool presents available indicators in a structured way. However, the indicator pool still has gaps, and it does not offer a recommendation which of the many indicators should be used. Further research may investigate which indicators ES experts and practitioners recommend to use. Such research could narrow down the indicator pool and present a second version of the library with only "best-selling" indicators. At the same time, the current gaps could be filled. In addition, the indicator pool provides only indicators for each step of the cascade, but it does not make the link to marine uses. A report by the Nordic Council uses expert judgement to assess how pressures from marine uses affect ES (Ivarsson et al., 2017), and recent studies explore the exposure of some marine ES to selected MSFD pressures and the dependencies between marine uses and ES (Bryhn et al., 2020; Depellegrin et al., 2020). Building on these studies and the indicator pool from this thesis, future studies could look into indicators to quantify the links between the marine uses and how they (negatively and positively) influence the ecosystem capacity to provide ES. The ecosystem capacity and quantification of ES is explored in this thesis by means of one marine use – mussel farming. Here, it would be interesting to explore in more detail to what extent existing studies about DEB models and aquaculture (or other) species provide DEB parameters that can be used to estimate ES provided by different aquaculture types.

The indicator pool can facilitate ES assessments. The MSP-SA provides an entry point for stakeholders into such assessments, and the marine planning framework for site selection highlights to which planning phases the ES concept can contribute. The thesis' findings will likely not contribute to the development of any plans in the near future considering that – at least in the EU – all plans have to be finalized by March 2021. Nevertheless, it would be interesting to test, e.g. the MSP-SA in a stakeholder setting to receive feedback – i.e. is it a valid approach to ask stakeholders about the benefits they (wish to) receive from a planning area as an entry point for ES assessments? *Von Thenen et al.* (submitted) suggest and provide evidence that it is a valid approach, but it has not been tested in an actual planning environment. Furthermore, when the plans are finalized in the EU, future research could evaluate the plans and investigate whether they have applied (aspects of) the ES concept in the process of developing the plans and to what extent the final, adopted, plans consider the results of any ES assessments carried out.

Monitoring and evaluation of plans is the last step in the MSP process (and can initiate the next planning cycle, cf. 1.1.1). However, evaluation can also be built into the planning process, and it is possible to have ex-ante, interim, and/or ex-post evaluation (Varjopuro, 2019a). The plans, furthermore, can be evaluated from a good governance perspective based on a number of social sustainability criteria (Varjopuro, 2019b). The thesis could not explore it in detail, but it is proposed that these criteria could include one on "inter-generational equity". Such criterion could include the notion of ecosystem goods and services in the following, proposed, definition: "The safeguarding of the provision of goods and services also for future generations." Thus, plans should not only be evaluated based on current stakeholder involvement and the extent to which their interests are taken into account but also in their consideration of the needs of future stakeholders. Such considerations do not only include that resources from the sea are used sustainably. It also includes that areas are set aside for nature protection to increase the resilience of marine ecosystems so that they can continue providing the ecosystem goods and services humans depend upon.

One common critique of the ES concept (cf. 1.1.2) is that only those ES are valued that have (economic) benefits for humans. On the one hand, this is a valid critique because the ES concept is dependent on how it is understood and implemented, and there can and has been a focus on economic valuation. On the other hand, it is expected that a focus on social sustainability, including equity now and in the future, has the potential to alleviate this critique. In addition, the ES concept does not replace the need for well-managed MPAs, in the author’s opinion, even though it can contribute to marine and biodiversity conservation (Ingram et al., 2012; Lester et al., 2020; Van der Biest et al., 2020). In a broader perspective, areas important for delivering ES and for protecting marine species and features can be considered in conjunction in a marine green infrastructure. Unlike the terrestrial green infrastructure, in the marine realm, it is understood as a network of areas that are important for biodiversity conservation, ecosystems’ health and resilience, and the provision of ES (Ruskule et al., 2019). The concept of marine green infrastructure came to the author’s knowledge at the MSP forum in Riga (MSP Forum, 2019b). While this thesis could not explore it in detail, it is envisioned that future EBM approaches to MSP are based on marine green infrastructures, where the ES concept will be included as one necessary contribution to develop a coherent network of areas important for marine conservation and human well-being.

CHAPTER 5. CONCLUSION

The objective of the thesis was to demonstrate how the ES concept can support and advance MSP. While MSP will certainly not solve all problems the oceans are facing today, the thesis postulates that integrating ES into MSP at least has the potential to alleviate conflicts in the marine environment and to communicate how the oceans contribute to human well-being. The focus of the research was on solving three challenges when it comes to the integration of ES in MSP, moving from the challenge of operationalizing ES for MSP, to data acquisition and analysis of ES with regard to one specific marine use, to a generalized framework that draws links between ES and MSP as a planning process and MSP site selection. The thesis contributes to an understanding of ES and how it can be linked to and support MSP while providing also some practical tools for actual ES assessments.

The first research question addressed the modification of ES frameworks and how such modification can facilitate the use of ES in MSP processes. The thesis proposes to use CICES to classify marine (a)biotic ES and the ecosystem cascade as a structuring framework for ES indicators. The thesis contributes to a clarification of the ES concept and the ecosystem cascade by providing a clear definition of the cascade steps and a thorough analysis of existing ES indicators. The indicator pool can support the data analyses part of an MSP process by focusing the stocktaking on the ecosystem components that currently provide ES and related benefits. Departing from the benefits that should be provided from a planning area can support the scenario development. The role of benefits and beneficiaries of ES is highlighted in the sustainability assessment framework (MSP-SA). The MSP-SA provides an entry point for stakeholder involvement. Stakeholders are important for the use of ES in MSP processes because their involvement can and should support decisions regarding which ES should be provided from a planning area. Focusing on the beneficiaries, and not just on marine users and the environment, furthermore, can contribute to increasing the social sustainability of marine plans. This focus on beneficiaries and social sustainability is a timely contribution to the scientific discussion. While a practical implementation of the MSP-SA remains to be tested, the thesis does present a first application to mussel farming.

The thesis used mussel farming as an example to explore the second research question, which asked about the environmental data that needs to be transformed to provide information on ES. Departing from the ecosystem cascade, the thesis shows that environmental data can be both combined and transformed. The combination of different environmental factors can provide information on the ecosystem capacity of a planning area to sustain mussel farming, and the transformation of parameters can quantify related ES. For the former, a GIS suitability analysis can be applied, which is generalized in the SPACEA toolbox that can analyze information of marine uses and environmental parameters in a planning area. The quantification of ES is achieved through the farm scale model that integrates the DEB model into the marine modelling framework FlexSem. DEB parameters exist for a range of other aquaculture species; therefore, it is a useful tool to provide information on ES that depend on species growth. Modelling of mussel growth provides estimates of potential harvestable biomass, nutrient removal, and impact on water transparency. These estimates can be compared to evaluate which potential mussel farming sites perform better and, hence, should preferably be selected as the optimal location. In the thesis, the approach was exemplified focusing on parameters that describe regulating ES, but it is proposed that it can include parameters such as biomass as an indicator for the provisioning ES as well.

A comparison based on ES to support aquaculture site selection – the third research question – therefore, can be approached from an instrumental perspective. Such a comparison, first, needs indicators for the ES, which can be supported by the indicator pool; second, it needs a method to provide estimates of the ES indicators, which can be accomplished by the DEB model (in the case of aquaculture species); third, it entails a site comparison, which can include a ranking of sites. Such site selection may be preceded by screening a planning area for its spatial availability and environmental suitability, which can be supported by GIS suitability analyses. The site selection, however, can also be embedded in the MSP process, and the generalized marine planning framework shows that the ES concept can support the formulation of a normative vision and strategic objectives for a planning area. The thesis, thus, contributes to an understanding of ES that goes beyond technical ES assessments and connects ES to essential steps in the MSP process. How such an understanding of ES can also support the evaluation of existing marine plans is proposed as future research, and it is suggested to include evaluation criteria targeted at sustainable use of ES.

The thesis shows that both MSP and ES have originated from a similar, conservationist, departure point and made a similar transition towards an economic focus. The thesis suggests that there are parallels in recent developments with a focus on social sustainability, which may lead to co-evolvement and further integration in the future. The thesis highlights pathways of integrating ES into MSP by contributing to an understanding of how ES in relation to MSP can be understood, by proposing entry points for stakeholder involvement, and by providing tools to facilitate and ease into ES assessments. The oceans and their ES are a common good, and the role they play for human well-being is recognized through the upcoming UN Decade for Ocean Science and Sustainable Development. The decade may support the advance of MSP towards social sustainability, and it provides an opportunity to emphasize the role of healthy and resilient marine ecosystems to provide ES now and in the future.

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APPENDICES

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Appendix A.

A structured indicator pool to operationalize expert-based ecosystem service assessments for marine spatial planning

Published in Ocean & Coastal Management:

von Thenen, M., Frederiksen, P., Hansen, H.S., Schiele, K.S., 2020. A structured indicator pool to operationalize expert-based ecosystem service assessments for marine spatial planning. Ocean Coast. Manag. 187, 105071. hhttps://doi.org/10.1016/j.ocecoaman.2019.105071

Appendix B.

Proposing an ecosystem services-based framework to assess sustainability impacts of maritime spatial plans (MSP-SA)

Accepted with minor revisions for publication in Ocean & Coastal Management

Appendix C.

Applying a combined geospatial and farm scale model to identify suitable locations for mussel farming

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von Thenen, M., Maar, M., Hansen, H.S., Friedland, R., Schiele, K.S., 2020. Applying a combined geospatial and farm scale model to identify suitable locations for mussel farming. Mar. Pollut. Bull. 156, 111254. https://doi.org/10.1016/j.marpolbul.2020.111254

Appendix D.

SPACEA: A Custom-Made GIS Toolbox for Basic Marine Spatial Planning Analyses

Published in Lecture Notes in Computer Science:

von Thenen, M., Hansen, H.S., Schiele, K.S., 2020c. SPACEA: A Custom-Made GIS Toolbox for Basic Marine Spatial Planning Analyses. In: Gervasi O. et al. (eds) Computational Science and Its Applications – ICCSA 2020. Lecture Notes in Computer Science, vol 12252, 394-404. Springer, Cham. https://doi.org/10.1007/978-3-030-58811-3_28

Appendix E.

Site selection of mussel mitigation cultures in relation to efficient nutrient compensation of fish farming

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Appendix F.

A generalised marine planning framework for site selection based on ecosystem services

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